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Alternate furrow irrigation of four fresh-market tomato cultivars under semi-arid condition of Ethiopia – Part I: Effect on fruit yield and quality

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Abstract

Scarcity of freshwater due to recurrent drought threatens the sustainable crop production in semi-arid regions of Ethiopia. Deficit irrigation is thought to be one of the promising strategies to increase water use efficiency (WUE) under scarce water resources. A study was carried out to investigate the effect of alternate furrow irrigation (AFI), deficit irrigation (DI) and full irrigation (FI) on marketable fruit yield, WUE and physio-chemical quality of four fresh-market tomato cultivars (*Fetan*, *Chali*, *Cochoro* and *ARP Tomato d2*) in 2013 and 2014. The results showed that marketable yield, numbers of fruits per plant and fruit size were not significantly affected by AFI and DI irrigations. WUE under AFI and DI increased by 36.7 % and 26.1 %, respectively with close to 30 % irrigation water savings achieved. A different response of cultivars to irrigation treatments was found for marketable yield, number of fruits and fruit size, WUE, total soluble solids (TSS) of the fruit juice, titratable acids (TA) and skin thickness. *Cochoro* and *Fetan* performed well under both deficit irrigation treatments exhibited by bigger fruit size which led to higher WUE. *ARP Tomato d2* showed good yields under well-watered conditions. *Chali* had consistently lower marketable fruit yield and WUE. TSS and TA tended to increase under deficit irrigation; however, the overall variations were more explained by irrigation treatments than by cultivars. It was shown that AFI is a suitable deficit irrigation practice to increase fresh yield, WUE and quality of tomato in areas with low water availability. However, AFI requires suitable cultivars in order to exploit its water saving potential.

Keywords: deficit irrigation, tomato (*Solanum lycopersicum* L.), tomato quality, water scarcity, water use efficiency

1 Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops worldwide and also among the important vegetable crops in Ethiopia with about 55,000 tons of fresh tomato produced on 7,000 ha annually (FAOSTAT, 2015). The demand for tomato has increased rapidly over the past years, as it has become the most profitable crop providing a higher income to small-scale farmers compared to other vegetable crops. However, the national average productivity is often low (7.9 t ha^{-1}), even below the African average (17.7 t ha^{-1}) - one reason for the fact that a substantial amount of irrigation water is required for tomato production. A better productivity is mandatory for sustainable increase in production. Moreover, increasing scarcity of freshwater along with forecasted increases in frequency and

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severity of drought caused by climate change (Evans & Sadler, 2008; Patanè *et al.*, 2011) and increasing competition from domestic and industrial uses (Strzepek & Boehlert, 2010) makes improving water use efficiency (WUE) in semi-arid and arid regions a primary concern.

Deficit irrigation (DI) is a strategy to increase on-farm water use efficiency (WUE) (Fereres & Soriano, 2007). There are, in principle, two DI techniques: regulated deficit irrigation (RDI) where a reduced amount of water is applied uniformly to the root-zone and partial root-zone drying (PRD), where the water is applied on a reduced area of the root-zone. The feasibility of both, RDI and PRD has been extensively studied in tomato with remarkable results in saving substantial amounts of irrigation water and increasing WUE (Zegbe *et al.*, 2006; Patanè & Cosentino, 2010; Patanè *et al.*, 2011). However, several other authors reported only marginal difference in yield response to PRD and well-watered greenhouse tomato (Campos *et al.*, 2009; Yang *et al.*, 2012). Also other benefits of PRD have been widely reported, namely promoting earlier crop maturity (Topcu *et al.*, 2007), enhancing fruit quality in terms of taste and flavour (Haghighi *et al.*, 2013), improving tomato plant resistance to disease (Xu *et al.*, 2009) and reducing the incidence of blossom end rot development (Sun *et al.*, 2013). On the other hand, also detrimental effects of PRD have been reported. Zegbe-Domínguez *et al.* (2003) and Casa & Rouphael (2014) found a significant reduction of processing tomato yields with PRD compared to a fully irrigated treatment. Similarly, Topcu *et al.* (2007) reported 20 % yield reduction as compared to full irrigation and saving about 50 % of irrigation water.

PRD was originally developed for micro irrigation systems. But meanwhile, it is also practiced as alternate furrow irrigation (AFI) in furrow irrigation studies. This irrigation technique is based on alternating wetting and drying of the opposite sides of the plant root system in subsequent irrigation events by watering one furrow and keeping dry the adjacent furrow until reversing in the next irrigation cycle. AFI has been proposed as a water saving technique with higher WUE without causing a significant yield reduction (Kang *et al.*, 2000). As furrow irrigation is one of the most widely used surface irrigation technologies in Ethiopia, AFI is the method of choice for small or medium scale vegetable production in areas where irrigation water is scarce. Though drip irrigation has a higher water saving potential compared to furrow irrigation, AFI is inexpensive, easy to implement and also avoids the cost associated to investment and management of drip irrigation (Casa & Rouphael, 2014). So far, AFI has been investigated in several cereal crops and grapes (Kang & Zhang, 2004; Du *et al.*, 2013; Jia *et al.*, 2014). Compared to conventional furrow irrigation, AFI saved 20–33 % irrigation water, shortened the time required for irrigation and substantially improved WUE. However, to our knowledge no experiments on the effect of AFI on field grown tomatoes have been reported until now.

Genotypic variations are not sufficiently addressed in most deficit irrigation studies and the studies conducted so far have generally focused on yield response of a single crop cultivar. A few studies compared response of maize and tomato genotypes under different deficit irrigations (Kaman *et al.*, 2011; Patanè *et al.*, 2014). Savic *et al.* (2011) found a variation in WUE and profit between two tomato cultivars under DI. A recent review by Chaves *et al.* (2010) has also highlighted that the efficiency of PRD or DI in modulating WUE depends on the varietal characteristics, soil type and prevailing weather conditions. The genotypic differences might be the result of differences in PRD-induced chemical signalling. Genotypes may also be different in the production of distinct fruit numbers and fruit sizes, which offers an opportunity to select water efficient genotypes depending on the kind of irrigation technique.

The use of different cultivars according to their level of tolerance to water stress employing DI strategies is a key for enhancing WUE in areas with growing water scarcity. Understanding responses of different cultivars to DI strategies is, therefore, necessary to optimize crop yield and quality of crops. In order to confirm whether alternate furrow irrigation is suitable for tomato cultivation and cultivars response differences, the study was conducted to investigate the agronomic response of four fresh tomato cultivars to moderate water deficit induced by AFI and DI under semi-arid condition of Ethiopia. The study is presented in two parts. Part I at hand addresses the agronomic response of tomato to deficit irrigation in terms of yield, WUE and quality. Part II presents the physiological response of tomato, which will allow additional insight to explain the agronomic response.

2 Materials and methods

2.1 Experimental site

The field experiment was carried out for two consecutive dry seasons in 2012/13 (thereafter 2013) and 2013/14 (thereafter 2014) from November to February and from December to May, respectively at Melkassa

Agricultural Research Center in the Central Rift Valley of Ethiopia (8°24′N, 39°21′E; 1,552 m asl). The climate of the area is semi-arid where rainfall is unpredictable in terms of onset, amount and distribution. Long-term (1977–2013) mean annual rainfall of the area is 829.5 mm, characterized by erratic inter-seasonal distribution, with a coefficient of variation of 28 % in August and 192 % in November. Weather data during the experimental periods is given in Table 1. The two growing seasons were different in rainfall amount and distribution. The rainfall amount was negligible in the growing season of 2013 whereas a total of 118 mm rainfall was recorded in March 2014 (Table 1). The average daily reference evapo-transpiration, ET_o (based on the Penman-Monteith FAO method), varied between 4.83 and 6.63 mm day^{-1} and total irrigation water was applied according to the irrigation treatments (Table 1).

The soil at the experimental field was a clay loam (sand 37 %, silt 42 %, and clay 21 %) moderately alkaline (pH 7.71) with low organic carbon (0.92–1.04 %), low to medium total soil nitrogen (0.058–0.080 %) and low available phosphorous (6.3–6.8 ppm) contents but with high extractable potassium (2.6–3.5 meq per 100 g soil). The volumetric soil moisture contents at field capacity (FC) and permanent wilting point (PWP) were 0.41 $m^3\,m^{-3}$ and 0.24 $m^3\,m^{-3}$, respectively. The total available water (TAW) between FC and PWP and readily available water (RAW) for a tomato root extracting depth of 0.60 m were estimated to be 102.4 mm and 41.8 mm, respectively. The depletion factor (p) for tomato, the average fraction of the TWA that can be depleted from the root zone before water stress occurs, was assumed as 0.40 (Allen *et al.*, 1998).

2.2 Plant material and growing conditions

Four fresh-market tomato cultivars, namely *Fetan*, *Chali*, *Cochoro* and *ARP Tomato d2*, were selected based on the similarity in phenology and growth habit from the rest of 27 tomato varieties that are officially recommended for commercial cultivation by Melkassa Agricultural Research Center. These table tomato cultivars are commonly grown in the central rift valley and other places in Ethiopia. The characteristics of the tomato cultivars used are given in Table 2.

Seedlings of these cultivars were raised in plastic trays containing peat moss for 24 days and transplanted to the experimental field on November 12, 2012 and December 27, 2013. Transplanting was performed manually at spacing of 0.4 m between plants and 0.9 m between rows. The plot size was 5.4 m × 4.0 m and each plot consisted of six rows and the middle four rows were used for data collection and final harvest. The distances between individual plots and between blocks were 1.5 and 4.0 m, respectively. A 1 m deep trench was constructed as a buffer-zone to prevent the lateral flow of irrigation water to the next experimen-

Table 1: *Mean monthly values of weather variables and the amount of irrigation water applied to full irrigation (FI), deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center.*

Month	*Average temperature* (°C)		*Relative humidity* (%)	*Cumulative daily wind speed* (km day^{-1})	*Sun shine* (hr)	ET_o (mm day^{-1})	*Total rainfall* (mm)	*Irrigation water applied* (mm)		
	Max	*Min*						*FI*	*DI*	*AFI*
2012/13										
November	29.5	9.5	50.1	222.7	10.2	5.41	0.0	254.2	254.2	254.2
December	28.4	10.9	52.3	233.6	9.7	5.07	0.0	304.6	242.2	242.2
January	28.2	10.1	55.3	216.9	9.0	4.83	0.0	130.5	65.7	65.7
February	30.7	11.7	45.0	247.9	9.9	6.09	0.6	102.1	51.1	51.1
Total							0.6	791.4	613.2	613.2
2014										
January	29.1	11.6	45.4	249.4	9.7	5.58	0.0	211.0	211.0	211.0
February	30.4	15.6	50.0	247.1	8.8	5.76	8.3	180.6	90.3	90.3
March	30.0	15.6	51.7	247.9	8.2	5.85	118.6	165.9	83.0	83.0
April	31.9	16.1	45.3	266.1	9.0	6.63	4.1	73.2	36.6	36.6
Total							131.0	630.7	420.9	420.9

Table 2: *Characteristics of fresh-market tomato cultivars used for study.*

Cultivar	*Growth habit*	*Fruit shape*	*Fruit size* (g)	*Maturity days*	*Yield* (t ha^{-1})	*Reaction to low water availability* *
Fetan	Short, determinate	Cylindrical	110–120	75–80	45.4	NA
Chali	Short, determinate	Round	80–85	80–90	43.1	NA
Cochoro	Short, determinate	Round	70–76	80–110	46.3	NA
ARP Tomato d2	Short, determinate	Flat	80–100	80–90	48.6	NA

Source: Ministry of Agriculture and Rural Development, 2009–2013. Crop variety registers. Addis Ababa, Ethiopia.
* NA. Data not available

tal plots. Phosphorus at the rate of 92 kg P_2O_5 ha^{-1} was applied at transplanting using DAP fertiliser, which also contains 36 kg ha^{-1} of N. Additional nitrogen was applied using urea at the rate of 46 kg N ha^{-1} in two splits (23 kg N ha^{-1} at transplanting and the remaining 23 kg N ha^{-1} at flowering as side dressing). Disease and insect pest were controlled by spraying appropriate pesticides, equally to all experimental plots. Weeding and cultivations were done manually.

2.3 Experimental design and irrigation treatments

All plants were initially well watered as pre-irrigation for the first six irrigation events to ensure a good establishment of seedlings and subsequent plant growth. Deficit irrigation treatments were commenced when the plants developed their first truss: 36 days after transplanting (DAT) in 2013 and 39 DAT in 2014. Irrigation water was applied by furrow irrigation in a 3–5 days interval for the first four weeks after transplanting and every seven days thereafter. The field irrigation application efficiency was assumed to be 45 %.The different irrigation treatments were (1) full irrigation (FI): crop water requirements applied uniformly to all furrows, (2) deficit irrigation (DI): 50 % of crop water requirement applied uniformly to all furrows, and (3) alternate furrow irrigation (AFI): 50 % of crop water requirement applied to every other furrow and alternating the furrows at each irrigation event. The crop water requirement was calculated as the difference between measured volumetric soil water content (θAC) and soil water content at field capacity (θFC). The amount of water applied to each plot was measured via a three inch throat width Parshall flume installed at the inlet of the experimental field.

In 2013, the dynamics of soil-water content (θ, vol%) were monitored *in-situ* at three depths (0–20, 20–40, and 40–60 cm) using a TRIME-PICO profile TDR Probe (IMKO, Germany), twice a week right before irrigation and 24 h after irrigation. A total of 20 TECANAT access tubes were installed down to a depth of 0.60 m along the side of the ridge equidistant between two plants. The average soil moisture content of FI treatment served as reference for the calculation of irrigation water needed for AFI and DI treatments. In the AFI treatment, two accesses tubes, one each on the left and right side, were placed to monitor soil moisture changes.

In 2014, 503DR neutron probe (CPN International, USA), previously calibrated for the experimental site, was used for monitoring soil moisture content. Eleven 0.80 m long access tubes were located per replicate, four in FI, three in DI and four in AFI plots. Soil moisture content was determined at depths of 0.15 m, 0.30 m, 0.45 m and 0.60 m. The top layer of 0.15 m was determined gravimetrically and then converted to volumetric water content by multiplying by bulk density of the soil (1.15 g cm^{-3}). The total of volumetric soil water content (m^3 m^{-3}) was summed up over the total rooting depth of 0.6 m.

The experimental lay out consisted in factorial combination of the four above mentioned commercial tomato cultivars and three irrigation treatments in a randomized block design with three replications.

2.4 Measurements

2.4.1 Agronomic data

Data on plant height and reproductive growth were collected from five tagged plants per plot. Plant height was measured at harvest. Mature and red ripe tomato fruits were manually harvested from the central four rows. Five harvests were carried out from 1st February to 8th March 2013 and from 1st April to 24th April 2014. Marketable fruit yield (tons ha^{-1}), numbers of fruit per plant and weight of 10 randomly selected fruits were recorded. Marketable and non-marketable yield were determined based on fruit size, presence of defects (malformed), disease and pest injuries. WUE was calculated as the ratio between marketable fruit yield and irrigation water applied. Total water use during the experimental period was the sum of irrigation water applied to each irrigation treatment in 2013 growing season. In 2014, effective rainfall was also taken into account.

2.4.2 Quality parameters

Ten ripe healthy fruits were randomly collected from each plot at the third harvesting time, weighed, washed and analysed for fruit quality traits. The following fruit biometric parameters were measured: fruit fresh weight, fruit longitudinal length, fruit width and skin thickness using a digital calliper (Harbor Freight Tools, USA). A fruit shape index was determined as the ratio between the fruit length and width. After measurements, juice was extracted by a juice extractor. The skin and solids were filtered out through muslin cloth and the juice content was expressed as ml juice per kg of fruit. The fruit juice extracts were analysed for pH, total soluble solids (TSS) and titratable acidity (TA). Juice pH was read with a Jenway 3520 pH meter (Bibby Scientific, UK) after standardization with buffer solutions of pH 4 and pH 7. TSS was determined using a TD-45 digital refractometer (Top Instrument, China). To determine TA, 10 ml of the extracted juice was thoroughly mixed with 50 ml of distilled water. Three drops of phenolphthalein as colorimetric indicator were added into each flask. The mixture was then titrated by adding 0.1 N NaOH. The volume of the sodium hydroxide, added to the solution, was multiplied by a correction factor of 0.064 to estimate TA as percentage of citric acid. TSS and TA were used to determine the sugar (TSS) and acid (TA) ratio as described by Beckles (2012). The determination was carried out in triplicate samples of each treatment.

2.5 Statistical analysis

Statistical analysis was performed through analysis of variance (ANOVA) using SAS statistical software of the SAS MIXED procedures (SAS Institute, 2004). Least significant difference (LSD) values at $P = 0.05$ were used to determine the significance of differences between treatment means.

3 Results

3.1 Dynamics of soil volumetric moisture contents

Changes in the volumetric soil water content (θ) of the irrigation treatments during the experimental periods are shown in Figure 1. Although the experiment was conducted during the dry season, there was a rainfall during 75–83 DAT in 2014 (Fig 1b), leading to an increase in soil moisture content of the deficit irrigation treatments. In both years, different irrigation treatments showed distinct soil moisture content patterns in the top 0.60 m soil layers except for the rainy period in 2014. In FI, θ during the entire experimental period remained higher than in AFI and DI. The value of θ in DI was 6.9 % and 12.6 % lower than the FI in 2013 and 2014, respectively. However, the value of θ in AFI fluctuated depending on the one-week wetting and drying cycle, with the irrigated side closer to field capacity during the first and second irrigation cycle then steadily lowered as compared to FI. Except during 75–83 DAT in 2014, the θ of the dry side of AFI was also significantly lower than the values of the other two treatments. Even though both DI and AFI treatments received the same total volume of irrigation water, slightly greater reduction in θ (expressed as average wet side and dry side) was observed in AFI, about 18.9 % and 23.4 % lower than FI in 2013 and 2014, respectively.

3.2 Effects of irrigation techniques on fruit yield and water use efficiency

Significant differences were found among cultivars for marketable fruit yield under the different irrigation techniques (Fig 2a & b). In 2013, *ARP Tomato d2* and *Cochoro* had the highest total fruit yield and marketable fruit yields under FI whereas *Cochoro* and *Fetan* were best performers under DI (Fig 2a). There was a different response of cultivars to deficit irrigation treatments. Relative to FI, *ARP Tomato d2* encountered a marked reduction in marketable fruit yield under both DI and AFI (Fig 2a). The yield reductions in *Chali* were significant in DI and not in AFI. The reductions were 23.9 % and 6.4 % in *Chali* and 16.9 % and 13.9 % in *ARP Tomato d2* under DI and AFI, respectively. The yield decrease was chiefly due to an increase of non-marketable fruits (Fig 3a). In 2014, *Cochoro* had the highest and *Chali* the lowest total and marketable fruit yields under all irrigation techniques (Fig 2b). On the other hand, *Fetan* grown under DI and AFI techniques, gave 32.2 % and 25.1 % more marketable fruit yield than under FI, respectively. *Fetan* had less fruits per plant but maintained bigger fruit size as compared to other cultivars (Table 3). The out performance of *Cochoro* over the other cultivars under deficit irrigation was mainly attributed to larger number of fruits per plant and medium-sized fruits (Table 3). *Fetan* and *ARP Tomato d2* had less non-marketable fruits resulted from better fruit size distribution and highest relative fruit growth under low soil water availability (Fig 3b). Poor performance of *Chali*, as exhibited by its lower yielding potential and higher share of non-marketable fruit, was attributed to lower number of fruits per plant and smaller fruit size.

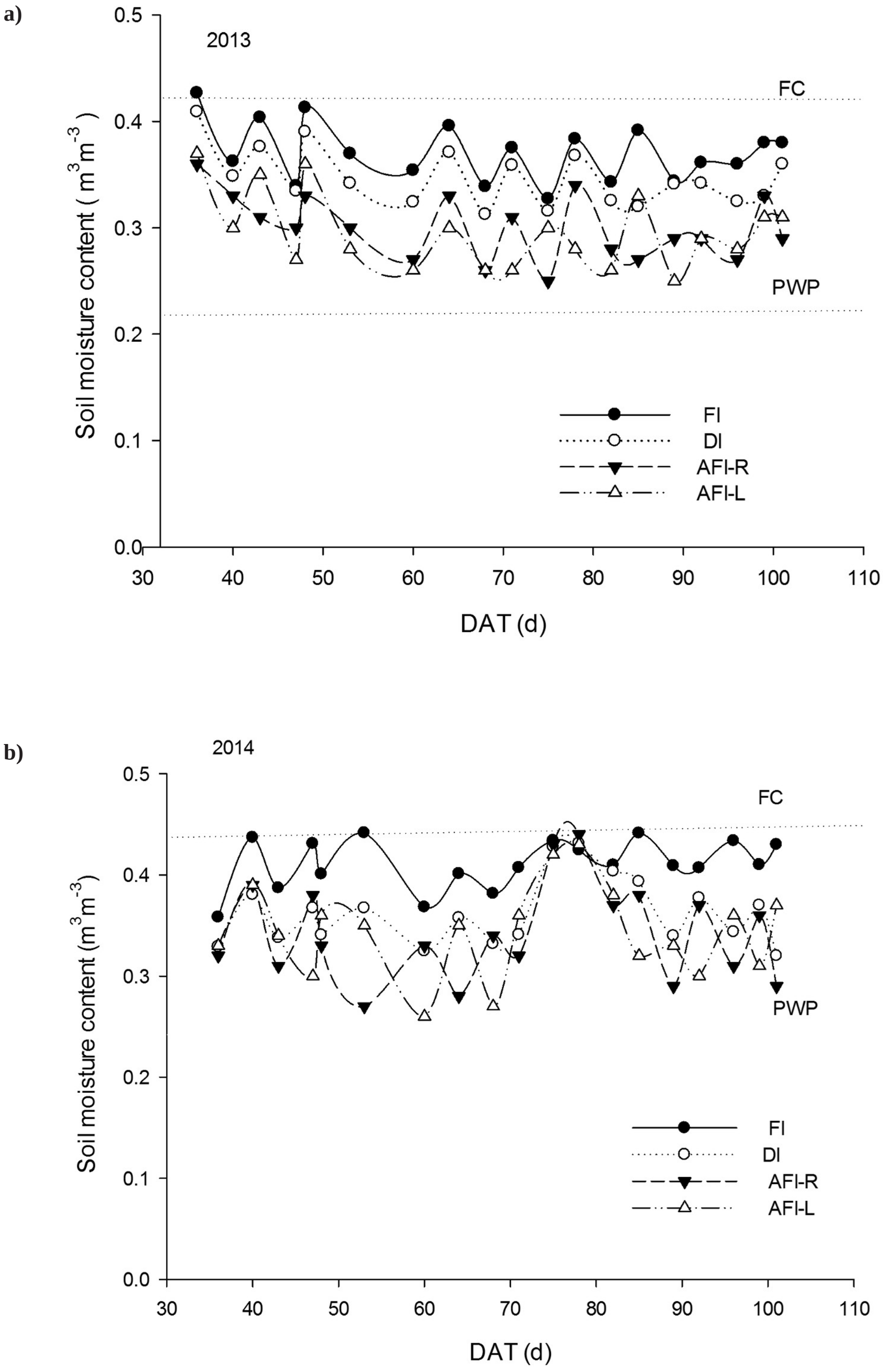

Fig. 1: *Soil moisture content vs. days after transplanting (DAT) under full irrigation (FI), deficit irrigation (DI) and right- and left-sides (AFI-right and AFI-left) of the plant root system of alternative furrow irrigation in 2013 (a) and 2014 (b) growing seasons at Melkassa Agricultural Research Center. FC=field capacity, PWP=permanent wilting point*

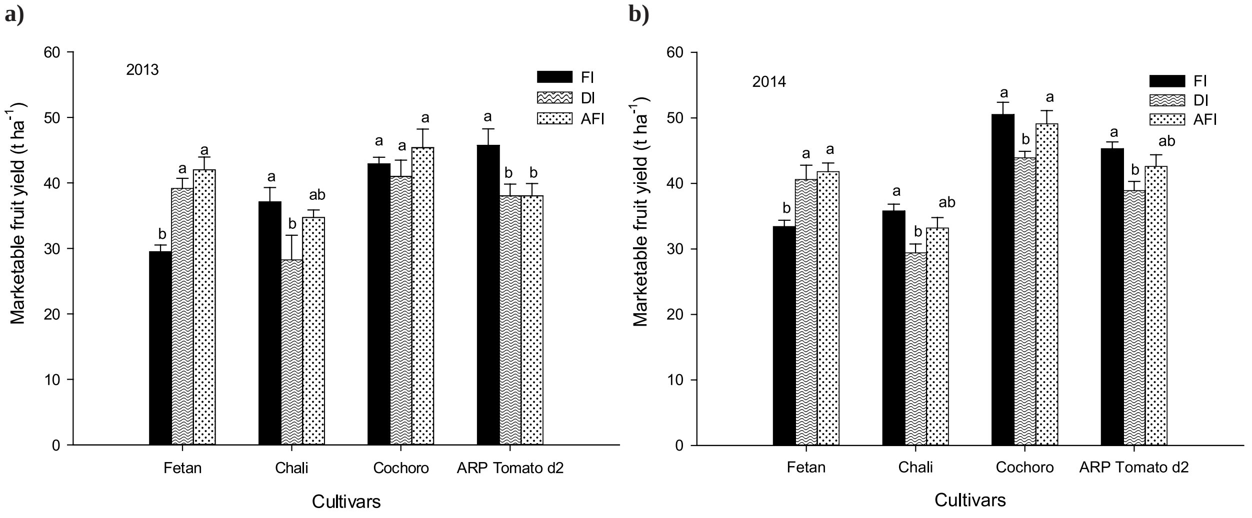

Fig. 2: *Marketable fruit yield of four tomato cultivars under full irrigation (FI), regulated deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center in 2013 (a) and 2014 (b) growing seasons. Values represent means ± SD (n=3) and mean bars of the same cultivar followed by the same letter are not significantly different (P < 0.05).*

Table 3: *Number of fruits per plant and average fruit weight of four tomato cultivars under full irrigation (FI), regulated deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center. Values represent means ± SD (n=3).*

Cultivar	*Number of fruits per plant*					*Average fresh fruit weight* (g)				
	FI	*DI*	*AFI*	*Mean*	*LSD* (5 %)	*FI*	*DI*	*AFI*	*Mean*	*LSD* (5 %)
2013										
Fetan	14.6±3.3	18.9±1.8	17.9±2.3	17.1	1.95	100.8±4.2	105.7±6.1	98.3±4.2	101.6	11.1
Chali	18.1±0.5	17.1±1.1	18.1±3.4	17.8	1.65	79.6±2.6	80.9±2.9	78.7±1.6	79.7	5.1
Cochoro	22.2±2.0	23.1±2.7	28.3±0.3	24.5	9.4	97.9±4.6	91.3±3.3	96.2±3.8	95.1	13.4
ARP Tomato d2	23.4±1.8	22.1±1.2	21.8±0.9	22.4	8.4	99.5±3.8	93.9±2.7	93.1±7.1	95.5	22.9
Mean	19.6	20.3	21.5			94.5	92.9	91.6		
LSD (5 %)	4.65	NS	7.58			14.66	9.32	6.29		
2014										
Fetan	15.8±3.7	18.1±0.8	21.8±0.8	18.6	5.6	92.3±5.3	92.2±1.7	88.1±1.0	90.9	5.4
Chali	18.6±2.8	17.9±0.8	17.5±1.5	18.0	3.7	73.9±4.3	65.3±0.6	75.2±0.5	71.5	5.7
Cochoro	32.3±1.7	24.6±1.0	27.6±1.2	28.2	7.5	95.2±1.6	102.3±4.9	95.3±4.7	97.6	5.5
ARP Tomato d2	19.4±1.1	20.9±0.7	22.9±1.1	21.1	2.2	86.4±5.0	82.9±4.6	94.9±6.1	88.1	10.1
Mean	21.5	20.4	22.5			86.9	85.7	88.4		
LSD (5 %)	3.08	2.84	2.62			9.46	7.92	8.86		

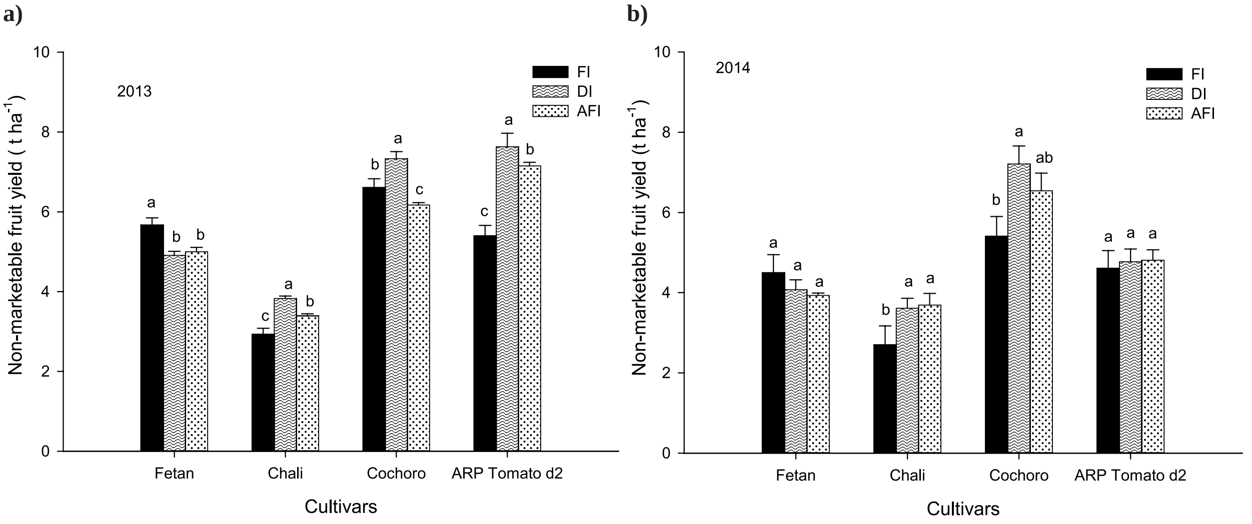

Fig. 3: *Non-marketable fruit yield of four tomato cultivars under full irrigation (FI), regulated deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center in 2013 (a) and 2014 (b) growing seasons. Values represent means ± SD (n=3) and mean bars of the same cultivar followed by the same letter are not significantly different ($P < 0.05$).*

WUE considerably varied among irrigation techniques as well as cultivars (Fig 4a and b). It ranged from 3.73 to 7.40 $kg\,m^{-3}$ and 4.70 to 9.80 $kg\,m^{-3}$ in 2013 and 2014 growing seasons, respectively. Compared to FI, 27.9 % irrigation water was saved with the use of AFI and DI thereby improving WUE of the cultivars under the two irrigation techniques by 36.7 % and 26.1 %, respectively. Despite the same amount of irrigation water applied, AFI resulted in significantly higher WUE than DI (Fig 4a and b). WUE of the four cultivars was also significantly different with the same trends as for the productivity differences. In 2013, WUE of *Fetan* and *Cochoro* was significantly increased under DI and AFI compared to FI. However, *Chali* and *ARP Tomato d2* did not exhibit significant increment in WUE. On the other hand, in 2014, WUE of all cultivars was significantly higher under deficit irrigation treatments as compared to FI (Fig 4b). Pronounced increments were recorded in *Fetan* and *Cochoro*. Overall, the WUE of *Fetan* was increased by 77.8 % and 72.3 % under AFI and DI as compared to FI, respectively. *Cochoro* also exhibited an increase of 46.3 % and 26.1 % WUE compared to FI. Similar to the 2013 results, *Chali* and *ARP Tomato d2* had lower WUE, but the WUE of both cultivars was significantly higher under DI (15.3 % and 13.6 %, respectively) and AFI (23.5 % and 28.2 %, respectively) as compared to FI.

The irrigation treatments and cultivars had significant effect on vegetative growth as determined by plant height at harvest (Table 4). Significantly highest plant height was obtained in FI and reduction in growth was evident under DI and AFI. However, cultivars differed in response to deficit irrigation and between seasons. In 2013, the vegetative growth of all cultivars was reduced under DI and AFI. In 2014, the vegetative growth of *Cochoro* and *ARP Tomato d2* was reduced significantly whereas it did not affected the vegetative growth of *Fetan* and *Chali*. Differences in fruit maturity periods were evident between years with fruits being ready for harvest after 82 and 91 days after transplanting (DAT) in 2013 and 2014, respectively. Nevertheless, deficit irrigation treatments had no significant effect on the maturity period for any of the cultivars in 2013 (Table 4) but it promoted earlier harvest in *Chali* and *ARP Tomato d2* in 2014. Over all, *Chali* was earlier mature while *Cochoro* was late by almost two weeks.

3.3 *Effects of irrigation techniques on physio-chemical quality*

Compared to the growing season 2013, the values of TSS and TA were lower in the 2014 (Table 5). TSS and TA were significantly higher under DI and AFI as compared to FI in both growing seasons. In 2013, TSS and TA were significantly higher in *Chali* and *Cochoro* under DI and AFI while the values of TSS and TA remained unchanged in *Fetan* and *ARP Tomato d2*. In 2014, TSS was significantly higher in all cultivars while TA increased only in *ARP Tomato d2*. However, years and irrigation treatments could explain 69.2 % and 11.5 % of the total variation of TSS in tomatoes fruits, respectively. Similarly, the total variation of TA and TSS was explained more by year variations and irriga-

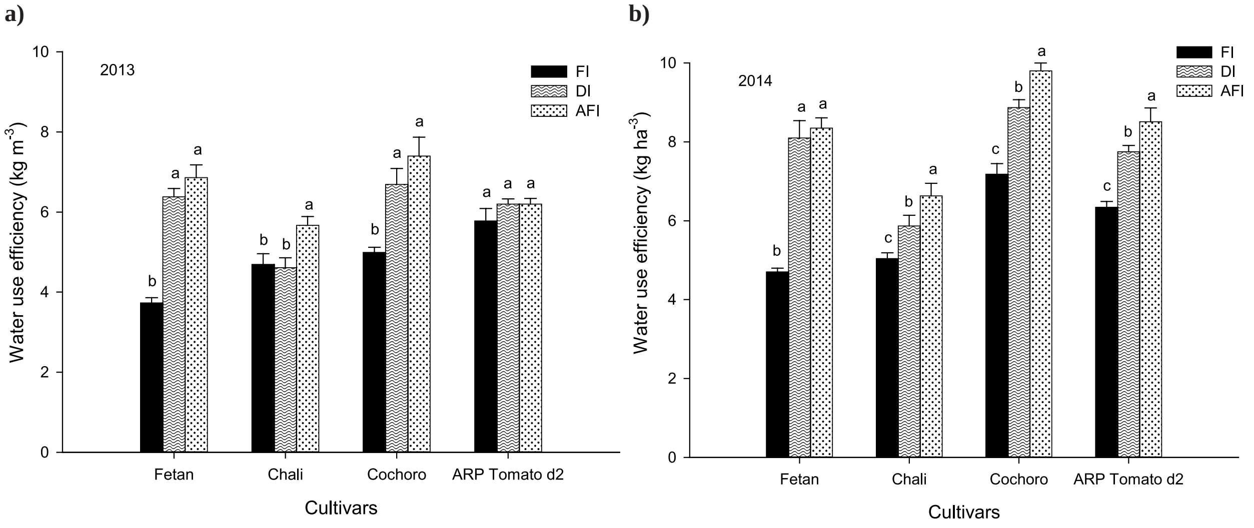

Fig. 4: *Water use efficiency (kg m^{-3}) of four tomato cultivars under full irrigation (FI), regulated deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center during 2013 (a) and 2014 (b). Values represent means ± SD (n=3) and mean bars of the same cultivar followed by the same letter are not significantly different ($P < 0.05$).*

Table 4: *Plant height and maturity period of four tomato cultivars under full irrigation (FI), regulated deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center. Values represent means ± SD (n=3).*

Cultivar	*Plant height* (cm)					*Maturity period* (days)				
	FI	*DI*	*AFI*	*Mean*	*LSD* (5 %)	*FI*	*DI*	*AFI*	*Mean*	*LSD* (5 %)
2013										
Fetan	81.6±2.6	74.7±1.9	75.4±3.4	77.2	4.1	105.9±0.7	106.7±1.2	107.7±1.5	106.8	2.2
Chali	78.1±2.0	66.1±3.2	66.2±2.3	70.1	8.9	98.6±0.2	97.5±0.9	95.4±0.5	97.3	1.4
Cochoro	88.9±2.8	76.7±1.6	72.2±3.3	79.3	2.7	109.9±1.0	110.4±1.0	109.2±1.6	109.8	3.0
ARP Tomato d2	86.7±2.8	71.1±3.8	73.3±3.5	77.0	10.4	102.6±0.7	103.4±1.3	108.5±0.8	104.8	2.6
Mean	83.9	72.2	71.8			104.3	104.5	105.3		
LSD (5 %)	8.8	5.1	7.9			1.34	1.25	2.7		
2014										
Fetan	74.3±0.7	68.3±2.2	68.6±1.3	70.4	17.8	99.5±3.5	102.0±5.6	98.1±4.0	99.9	4.3
Chali	70.4±1.0	65.6±1.4	67.7±1.6	67.9	6.1	97.5±6.8	91.5±1.3	93.8±4.9	94.3	5.8
Cochoro	81.1±1.9	69.4±1.0	67.4±2.0	72.6	9.7	109.2±3.5	105.2±5.0	108.0±1.7	107.5	10.1
ARP Tomato d2	87.3±1.1	67.3±0.8	71.2±1.8	75.3	9.5	105.1±2.9	97.7±3.4	99.5±3.5	100.8	3.9
Mean	78.3	67.7	68.7			102.8	96.6	99.9		
LSD (5 %)	2.8	13.6	6.1			4.47	6.11	3.24		

Table 5: *Physio-chemical characteristics of four tomato cultivars under full irrigation (FI), regulated deficit irrigation (DI) and alternate furrow irrigation (AFI) at Melkassa Agricultural Research Center. Values represent means ± SD (n=3).*

	Cultivar	*Quality parameter*	*FI*	*DI*	*AFI*	*LSD (5 %)*
2013	*Fetan*	Fruit skin thickness (mm)	5.42 ±0.5	5.79 ±0.70	5.79 ±0.49	NS
		Juice content (ml/kg)	1049.0±15.2	1054.3±25.2	1046.3±15.2	NS
		Total solid soluble (Brix)	4.07±0.1	4.00±0.10	4.07±0.12	NS
		Titratable acid (%)	0.48±0.02	0.51±0.02	0.50±0.02	NS
		TSS:TA ratio	8.46±0.13	7.84±0.82	8.11±0.55	NS
	Chali	Fruit skin thickness (mm)	6.96±0.19	5.92±0.47	6.19±0.69	NS
		Juice content (ml/kg)	1049.2±13.5	1052.6±13.5	1053.1±13.5	NS
		Total solid soluble (Brix)	3.33±0.13	3.70±0.10	3.93±0.12	0.211
		Titratable acid (%)	0.55±0.05	0.59±0.03	0.66±0.03	0.091
		TSS:TA ratio	6.16±0.79	6.31±0.49	6.19±0.14	NS
	Cochoro	Fruit skin thickness (mm)	5.66±0.34	5.95±0.62	7.13±0.61	1.39
		Juice content (ml/kg)	1082.7±9.4	1036.0±9.4	1051.1±9.4	37.1
		Total solid soluble (Brix)	3.82±0.20	4.07±0.12	4.27±0.01	0.35
		Titratable acid (%)	0.52±0.01	0.54±0.04	0.59±0.01	0.06
		TSS:TA ratio	7.61±0.18	7.59±0.25	6.84±0.56	NS
	ARP Tomato d2	Fruit skin thickness (mm)	5.21±0.68	5.63±0.01	6.76±0.29	1.32
		Juice content (ml/kg)	1040.7±11.4	1059.1±11.4	1048.5±11.4	NS
		Total solid soluble (Brix)	3.86±0.13	3.93±0.12	4.00±0.20	NS
		Titratable acid (%)	0.53±0.01	0.50±0.01	0.58±0.01	0.075
		TSS:TA ratio	7.31±0.18	7.82±0.25	6.89±0.25	0.82
2014	*Fetan*	Fruit skin thickness (mm)	6.10±0.85	6.67±0.90	7.13±0.84	0.98
		Fruit diameter (mm)	56.8±0.78	54.3±0.77	56.0±0.75	NS
		Fruit length (mm)	61.0±0.73	55.1±0.73	55.8±0.70	NS
		Fruit shape index	0.94±0.02	0.99±0.02	1.01±0.02	NS
		Juice content (ml/kg)	1130.9±10.5	1111.4±10.5	1133.4±10.5	NS
		pH	4.49±0.05	4.46±0.06	4.49±0.04	NS
		Total solid soluble (Brix)	2.78±0.03	3.11±0.03	3.27±0.01	0.016
		Titratable acid (%)	0.48±0.03	0.49±0.02	0.51±0.04	NS
		TSS:TA ratio	5.88±0.19	6.38±0.19	6.46±0.19	NS
	Chali	Fruit skin thickness (mm)	6.90±0.78	6.37±0.84	6.03±0.84	NS
		Fruit diameter (mm)	57.9±0.77	58.1±0.77	59.6±0.75	NS
		Fruit length (mm)	50.8±0.73	50.8±0.73	50.9±0.70	NS
		Fruit shape index	1.14±0.02	1.14±0.02	1.17±0.02	NS
		Juice content (ml/kg)	1105.9±10.5	1095.8±10.5	1126.0±10.5	NS
		pH	4.52±0.04	4.55±0.09	4.54±0.09	NS
		Total solid soluble (Brix)	3.10±0.05	3.25±0.05	3.63±0.05	0.27
		Titratable acid (%)	0.54±0.01	0.52±0.02	0.53±0.01	NS
		TSS:TA ratio	5.80±0.24	6.22±0.14	6.70±0.66	0.71
	Cochoro	Fruit skin thickness (mm)	6.05±0.35	6.77±0.35	7.10±0.35	1.01
		Fruit diameter (mm)	61.6±0.77	63.5±0.77	61.4±0.75	NS
		Fruit length (mm)	54.7±0.73	51.2±0.73	52.7±0.70	NS
		Fruit shape index	1.13±0.02	1.24±0.02	1.17±0.02	NS
		Juice content (ml/kg)	1057.7±13.0	1064.9±13.0	1065.9±10.5	NS
		pH	4.56±0.11	4.53±0.010	4.51±0.07	NS
		Total solid soluble (Brix)	2.95±0.06	3.02±0.02	3.63±0.02	0.28
		Titratable acid (%)	0.41±0.01	0.45±0.01	0.44±0.01	NS
		TSS:TA ratio	7.22±0.23	6.88±0.23	8.22±0.19	NS
	ARP Tomato d2	Fruit skin thickness	6.00±0.73	5.29±0.73	6.70±0.53	NS
		Fruit diameter	62.2±0.77	57.6±0.77	59.6±0.75	NS
		Fruit length	58.4±0.73	56.4±0.73	57.4±0.70	NS
		Fruit shape index	1.07±0.02	1.02±0.02	1.04±0.02	NS
		Juice content (ml/kg)	1087.9±9.1	1102.0±9.1	1091.3±10.5	NS
		pH	4.55±0.06	4.44±0.09	4.48±0.09	NS
		Total solid soluble (Brix)	2.89±0.01	3.12±0.01	3.46±0.01	0.13
		Titratable acid (%)	0.46±0.02	0.50±0.02	0.53±0.02	0.037
		TSS:TA ratio	6.30±0.19	6.23±0.17	6.54±0.17	NS

tion treatments than variations due to cultivars. In general, tomato grown under AFI had the highest TSS and TA. A negative but non-significant correlation was noted between fruit yield and TSS. Nevertheless, fruit biometric parameters (fruit size, fruit length, fruit width, and fruit shape index), pH and sugar acid ratio were not significantly influenced by irrigation treatments. However, a significant reduction of juice content under both deficit irrigation treatments was observed in *Cochoro*. The fruit skin thickness was increased under both DI and AFI as compared to FI, but the response varied among cultivars and years. In 2013, the fruit skin thickness of *Cochoro* and *ARP Tomato d2* were increased while it was not affected in *Fetan* and *Chali*. In 2014, *Fetan* and *Cochoro* had significantly higher skin thickness under DI and AFI as compared to FI. However, other fruit biometric parameters (fruit length and fruit width) and pH were not affected by deficit irrigation treatments (Table 5). The pH of the juice ranged from 4.46 to 4.55 and exceeds the minimum permissible level ($\mathrm{pH} < 4.30$) to define the product as ‘good’ according to the reference of analytical scales for processing tomatoes (Patanè & Cosentino, 2010).

4 Discussion

The results of this study show that the comparison of different cultivars with respect to their performance under different irrigation regimes is necessary to evaluate both water saving potential and yield expectation. This is especially true for crops with high breeding activities and frequent occurrence of new varieties such as tomato, where there is a high cultivar-to-cultivar variation in response to deficit irrigations as a function of stress tolerance levels (Kaman *et al.*, 2011; Patanè *et al.*, 2014). This underlines the necessity that optimisation of the plant available soil water should be done for a particular cultivar and not for a species in general, as suggested by Savic *et al.* (2011). Obviously, the cultivars specific fruit size distribution are crucial for the final marketable yield, as demonstrated by Xu *et al.* (2009) who found that fruit yield of large fruit-sized tomato cultivars can be increased under PRD but not the fruit yield of the cherry tomato cultivar.

Deficit irrigation during early reproductive stages often causes abnormal reproductive organs and results in failure of pollination and fruit abortion consequently reducing yield (Pulupol *et al.*, 1996; Zegbe *et al.*, 2006). However, cultivars employ different strategies to adapt to the water stress induced by deficit irrigation. *Cochoro* and *ARP Tomato d2* had considerably higher yields under full irrigation. *Cochoro* and *Fetan* performed well under both deficit irrigation treatments leading to higher levels of WUE. As the higher yield of *Cochoro* was due to both greater number of fruits per plant and bigger fruit size, it is concluded that this cultivar is well adapted to water stress. Similarly, the local cultivar *Fetan* had bigger fruit size but less fruit numbers and performed well under DI and AFI. Both cultivars are considered to be recommendable for potentially drought affected production systems, but with a generally higher yield potential of *Cochoro* than *Fetan*. Moderate fruit numbers and medium fruit size contributed to the higher yields in *ARP Tomato d2*, a cultivar which is best suited for the production under sufficient irrigation. The production potential of genotypes may play an important role in WUE variation under water deficit conditions (Grant *et al.*, 2010; Kaman *et al.*, 2011). Drought resistant crop cultivars have been reported to improve WUE, however, crops with higher drought resistance are often associated with lower crop yield (Blum, 2005). Nevertheless, it is noted that cultivars with higher marketable yields were generally associated with higher WUE. In this study, *Fetan* and *Cochoro* showed the highest marketable yield as well as higher WUE under DI and AFI. *Chali* consistently had lower marketable fruit yield and as consequence, with lowest WUE across the irrigation treatments. Therefore, under given limited water resource, cultivars with highest marketable fruit yield potential are superior in WUE, suggesting that cultivars with higher WUE thus combined both drought avoidance mechanisms and higher productivity. As low yielding cultivar, *Chali* has excellent handling properties and taste quality, e.g. a ticker fruit skin and higher TA; the variety is widely produced in Ethiopia and has good market potential. In this experiment it was shown that *Chali* performs best when well-irrigated. Consequently, *Chali* responded with better taste quality in terms of higher TSS and TA in the 2014 season, were unexpected rainfalls changed the water supply pattern.

In general it can be stated that the fruit yield increase observed under AFI was mainly attributed to the increase in number of fruits than to mean fruit size concurring with previous reports (Pék *et al.*, 2014). Besides saving substantial irrigation water, AFI improves WUE over DI and FI, what is also reported in other studies (Kirda *et al.*, 2007; Topcu *et al.*, 2007). Mean fruit size, fruit diameter and length are mainly determined by genotype but they are also affected by irrigation amount to some extent (Patanè & Cosentino, 2010; Liu *et al.*, 2013). The study showed that deficit irrigation treatments had promoted earlier harvest but the response was different between cultivars and growing season. Previous reports also showed that deficit irrigation has shortened (Zegbe-Domínguez *et al.*, 2003) or did not modify the maturity period (Casa & Rouphael, 2014). Overall variations in fruit quality parameters were more explained by irrigation treatments than by cultivar. TSS and TA, the biochemical fruit quality traits which contribute to the flavour of fresh tomatoes (Panthee *et al.*, 2013), increased significantly under deficit irrigation treatments, concurring several earlier reports (Zegbe-Domínguez *et al.*, 2003; Patanè & Cosentino, 2010). These increases are mainly due to reduced water content and concomitant increase in dry matter that leads to higher solute concentration of fruits (Pulupol *et al.*, 1996; Haghighi *et al.*, 2013). Water deficit initiated during flowering and fruit set reduces the number of reproductive organs but may increase quality due to increased availability of assimilates for the remaining fruits (Patanè & Cosentino, 2010). The response of TSS and TA toward deficit irrigation differs between cultivars. *Chali* was low yielding under deficit irrigation but had higher TSS and TA than other cultivars. Tomato fruits under AFI had also higher values of TSS and TA than those under DI and FI. Water deficit before or during repining has been reported to increase TSS and TA of tomato (Zegbe-Domínguez *et al.*, 2003; Sun *et al.*, 2014) or had no effects (Campos *et al.*, 2009). The responses of fruit quality parameters differ considerably depending on the differences in genotypes, stress intensity and phonological stages at which deficit irrigation was imposed (Ripoll *et al.*, 2016). TSS content was found to depend on cultivar but seasonal environmental variations during the fruit repining stages may also influence the contents.

5 Conclusion

The result of the present study confirmed that, in general, AFI has the potential to save close to 30 % of irrigation water relative to full irrigation, greatly improving WUE, some fruit quality aspects (TSS, TA) and postharvest handling properties (fruit skin thickness) without causing a detrimental effect on the fruit yield under the studied semi-arid climate of Ethiopia. It was further shown that cultivars respond differently to irrigation treatments. This demonstrates the need for cultivar specific irrigation management practices. *Cochoro* and *Fetan* performed well under AFI, while *Chali* and *ARP Tomato d2* performed relatively better under full irrigation. Cultivars with highest marketable fruit yield have better WUE suggesting that the selection of suitable cultivar for different irrigation methods is crucial for improving WUE in areas with water scarcity.

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