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Growth, fruit yield and quality of tomato (*Lycopersicon esculentum* Mill.) as affected by deficit irrigation regulated on phenological basis

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ABSTRACT

A field experiment was conducted for two years (2013–15) to evaluate the response of tomato (*Lycopersicon esculentum* Mill.) to deficit irrigation (DI) with drippers. The options tried were either the regulated DI on the basis of climatological approach i.e. irrigation water equalling 0.6, 0.8 and 1.0 times the evapotranspiration (ET) or DI (0.6xET) at phenological stages (vegetative, flowering, fruiting, vegetative-cum-flowering, vegetative-cum-fruiting and flowering-cum-fruiting stages) and disrupting irrigation (15 days) at either of vegetative, flowering and fruiting stage. Compared with the full irrigation (FI; 78.0 Mg ha^{-1}) the regulated deficit irrigation though did not affect the marketable fruit yield (MFY) at $RDI_{0.8,}$ there was loss of about one-fourth MFY with $RDI_{0.6.}$ Nevertheless the water productivity (19.2 kg m^{-3}) was the maximum under $RDI_{0.8.}$ When the deficit irrigation was applied at different growth stages, MFY was rather improved by 4% with $DI_{0.6(VS)}$ while $DI_{0.6(FL)}$ showed little effect and a decline of 7% was monitored with $DI_{0.6(FT).}$ The DI applied at either of two stages ($DI_{0.6(VS+FL)}$; $DI_{0.6(FL+FT)}$; $DI_{0.6(VS+FT)}$) resulted in 14–18% decline in MFY. The crop was able to tolerate interruptions of irrigation for 15 days at the above phenological stages i.e. simulating canal closures and the decline in yield was only 3–7%, the highest being at fruiting stages (II_{FT}). The major advantage of DI was improvement in quality in terms of total soluble solid, ascorbic acid, acidity and colour index (lycopene) though the fruit size was affected. It was concluded that benefits of deficit irrigation in terms of improved quality and water productivity while sustaining fruit yield could be achieved with regulated DI at 0.8xET and DI at 0.6xET during vegetative stage followed by flowering.

1. Introduction

Tomato (*Lycopersicon esculentum* Mill.) is an important vegetable and has the highest area under cultivation among vegetables in the world. Since it has high water requirement, scarcity of water is the main constraint for its production in the arid and semi-arid areas. World over, the priority is now on the adoption of appropriate irrigation strategies those help in saving irrigation water without compromising on yield (Pereira et al., 2002; Patanè et al., 2011; Costa et al., 2007; Favati et al., 2009). Deficit irrigation (DI) is a strategy that involves irrigating the root zone with less water than required for evapotranspiration (Zegbe-Dominguez et al., 2003). Under DI, crops are deliberately exposed to certain level of water stress either during a particular period or throughout the growing season (Topcu et al., 2007; Pereira et al., 2002). DI is useful in reducing production costs, water consumption and minimizing leaching of nutrients and pesticides in ground water (Pulupol et al., 1996). Therefore, adoption of DI can make substantial contribution to save water (Zegbe-Dominguez et al., 2003; Costa et al., 2007).

Effects of different irrigation intervals, amounts, and techniques have also been extensively tested on tomato in terms of its yield and fruit quality (Zegbe-Dominguez et al., 2003; Kirda et al., 2004; Harmanto et al., 2005). Identification of its critical irrigation stage and scheduling of irrigation based on crop water status seems to be the most cost efficient way to improve water use efficiency (Ngouajio et al., 2007). Kirda et al. (2004) reported that deficit irrigation practice in tomato increased water use efficiency (WUE) with only marginal yield reduction. However, all the stages of development in tomato are not equally sensitive to soil moisture deficit, and deficit irrigation during non-critical stages may be more beneficial. The flowering and fruit setting stages are the most sensitive to water deficits (Harmanto et al., 2005). Thus, a better understanding of the relationships among soil water deficit, physiological manifestation and fruit yield should enable growers

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Table 1
Mean monthly weather conditions during the first and second season of tomato.

Month	Tmax (°C)	Tmin (°C)	RHmax (%)	RHmin (%)	WS ($km h^{-1}$)	Rainfall (mm)	Pan-E (mm)
2013–14							
November	30.1	16.2	86	35	5.6	1.3	4.4
December	28.7	12.7	88	30	5.2	1.5	3.5
January	29.0	13.9	86	33	5.5	0.0	3.6
February	30.5	14.0	80	26	6.0	0.8	4.8
2014–15							
October	32.0	19.5	82	39	5.5	26.1	5.1
November	30.3	16.8	96	38	5.0	44.0	4.5
December	28.3	12.3	97	35	4.5	7.6	3.6
January	28.7	12.6	95	30	4.1	0.1	3.9

T, RH, WS, PAN-E denote temperature, relative humidity, wind speed and open pan evaporation, respectively.

to efficiently manipulate irrigation water management (Renquist and Reid, 2001). In addition, the effect of DI at various growth stages especially withholding of water at specific stage of tomato and its influence on water productivity and quality traits of tomato has not been documented coherently. Keeping above in view, the effects of DI regimes either regulated or at phenological stages along with disruption of irrigation were assessed in terms of growth, biomass, fruit yield, water productivity and quality traits of tomato.

2. Materials and methods

2.1. Experimental details

The experiment was carried out for two consecutive years (2013 & 2014) at the research farm of National Institute of Abiotic Stress Management (NIASM), Baramati, Pune, Maharashtra, India (latitude: 18°09′N, longitude: 74°30′E, elevation of 550 MSL). The experimental site was highly prone to drought and characterized by low and erratic rainfall. The long term annual rainfall is 588 mm of which about 71% is received during the four months of southwest monsoon season (June-September). Some of the weather parameters as monitored at automatic weather station (AWS) are included in Table 1. Monthly means of air temperature were 20.3 and 26.6 °C during growth period of two years. The coarse (21% < 2 mm) and shallow (0.45 m) soil at the experimental site was derived from basaltic parent material. The soil moisture constants i.e. field capacity (−0.03 MPa) and permanent wilting point (−1.5 MPa) were 0.19 and 0.07 $g g^{-1}$, respectively.

The field was initially ploughed and this followed harrowing (twice) to pulverize the soil. Well decomposed spent mushroom substrate (10 $Mg ha^{-1}$) was added prior to second harrowing. Thereafter, ridges and furrows were created using a mini tractor. Twenty-five days old seedlings (3–4 leaf stage) of tomato (cv. Ryna®) were transplanted keeping a distance of 0.40 m between plants and 0.90 m between rows. Transplanting date was 29th October during 2013 and 28th September in 2014. For drip irrigation, single lateral line of 16 mm diameter LLDPE pipes was laid along the each row of the crop. The laterals were provided with inline dripper of 4 lph discharge capacity at a pressure of 1 $kg cm^{-2}$ and spaced at a distance of 0.40m. The average emission uniformity of drip irrigation system was estimated as 90 per cent. After common (50 mm) irrigation at transplanting, the drip irrigation was initiated at 10 days after planting. The amount of water to be applied through drip irrigation was calculated by the climatological approach method (Doorenbos and Pruitt, 1977). Reference crop evapotranspiration (ETr) was computed on a daily basis using Penmann-Monteith approach (Allen et al., 1998) wherein ground heat flux was approximated as 12% of the net radiation based on observations on the shallow basaltic soil of the locality. Crop coefficient utilized were those obtained in a similar environment, with

Table 2
Irrigation water applied under different treatments during the two years.

Mode of drip irrigation	Total irrigation water applied (cm)	
	2013–14	2014–15
a) Regulated deficit irrigation		
0.6xETc [$RDI_{0.6}$]	32.5	25.4
0.8xETc [$RDI_{0.8}$]	39.5	32.0
1.0xETc [FI]	46.4	38.6
b) FI except DI (0.6xETc) at growth stage		
Vegetative [$DI_{0.6(VS)}$]	42.9	33.9
Flowering [$DI_{0.6(FL)}$]	41.7	34.9
Fruiting [$DI_{0.6(FT)}$]	40.7	33.8
Veg. & Flower [$DI_{0.6(VS+FL)}$]	38.2	30.2
Veg. & Fruiting [$DI_{0.6(VS+FT)}$]	37.2	29.1
Flow. & Fruiting [$DI_{0.6(FL+FT)}$]	36.0	30.1
c) FI except irrigation interrupted (15 d) during growth stage		
Vegetative [II_{VS}]	42.1	31.5
Flowering [II_{FL}]	40.8	33.5
Fruiting [II_{FT}]	40.6	34.7

Vegetative, flowering and fruiting stage correspond to 15–59, 51–80 and 81–120 days after transplant (DAT).

the values of 0.35 from transplant up to establishment, 0.55 up to the early stages of blooming; 0.90 during blooming-fruit setting; 1.1 during berry growth-fruit maturity and 0.85 from the maturity to final harvest of fruits. Considering the crop factor as per stages and wetted area factor, the ETc and thereby daily water requirement of the crop was computed using following equation (Pawar et al., 2013); $ETc = ETr \times Kc \times Ls \times Es \times Wa/\eta$, where, ETc volume of water applied ($l\ d^{-1}\ plant^{-1}$); ETr, Reference evapotranspiration ($mm\ d^{-1}$); Kc, Crop coefficient; Ls and Es, lateral and emitter spacing; Wa, wetted area factor; η emission uniformity of the drip system. The twelve treatments imposed in a randomized complete block design with four replications consisted of: a) applying irrigation water 0.6xETc ($RDI_{0.6}$; T_1) throughout, regulated deficit irrigation 0.8xETc ($RDI_{0.8}$;T_2) throughout, equalling irrigation water 1.0xETc (Full irrigation, FI, T_3) throughout, b) FI except $DI_{0.6}$ at phenological stages viz. vegetative ($DI_{0.6(VS)}$; T_4), flowering ($DI_{0.6(FL)}$; T_5), fruiting ($DI_{0.6(FT)}$; T_6), vegetative-cum-flowering ($DI_{0.6(VS+FL)}$;T_7), vegetative-cum-fruiting ($DI_{0.6(VS+FT)}$; T_8), and flowering-cum-fruiting ($DI_{0.6(FL+FT)}$; T_9) stages and c) FI except interruption of irrigation (15 days) either at vegetative (II_{VS}; T_{10}), flowering (II_{FL}; T_{11}) and fruiting (II_{FT};T_{12}). The period of vegetative, flowering and fruiting stages corresponded to 15–59, 51–80 and 81–120 days after transplanting (DAT). The plot size was 10.0 m × 4.5m. Total water applied in different irrigation treatments varied between 32.8–46.4 cm during 2013–14 and 25.4–38.6 cm during 2014–15 (Table 2). Fertilizers consisted of a basal dose of 75, 50 and 50 $kg ha^{-1}$ of N, P and K, respectively followed by fertigation with 75, 50 and 50 $kg ha^{-1}$ of N, P and K that were applied in 5 equal splits at fortnight interval. Secondary nutrient mixture, having Ca, Mg and S was also applied twice 20 kg ha^{-1} during flowering (60 DAT) and fruiting stages (90 DAT). The plants were vertically supported with plastic wires running at different height along the rows. Recommended package of practices were followed for weed and pest control etc.

2.2. Growth and yield

Plant height, stem girth, days to flowering and days to fruiting were monitored from ten randomly tagged plants for each replication. The ripened fruits (about 70–80% pink stage) were picked up manually from each plot. These were washed with running water and dried thoroughly with absorbent paper before monitoring fresh fruit weight. After recording total fruit weight, the red and disease free, well graded fresh and firm fruits were carefully chosen for marketable yield. The procedure was repeated after each picking (total 6–7 pickings). Sub-samples from 10 plants in each plot were also drawn for recording polar (blossom end to stem scar) and equatorial diameter. Ripened fruits of the 2nd and 3rd picking were sampled (30 fruits per plot) for quality analysis. For estimation of biomass yields five plants were sampled, partitioned into stem plus leaves and roots. These were dried at 60 °C until constant weight. Soil samples were drawn to a distance of 0.4 m from the base of the plant (0.10 m interval) and 0.6 m depth (0.15 m interval) and washed to determine root weight and length.

2.3. Physiological parameters

Chlorophyll content was estimated at fruiting stage (95 DAT) to get the impact of water stress applied at various phenological stages. Leaf discs were taken from five fully expanded leaves of comparable physiological age and the total chlorophyll concentration (Chl a+ Chl b) was analysed following the procedure described by Hiscox and Israelstam (1979). LAI was recorded during clear sunshine hours from 11 am to 1 pm at fruiting stage (90 DAT) with Ceptometer (AccuPAR LP-80, Decagon Devices Inc., USA). Advance Photosynthetic System *GFS-3000* (WALZ, Germany) was used to monitor various physiological parameters like photosynthetic assimilation rate, water vapour conductance and transpiration rate. These parameters were recorded on clear sunshine hours during 11 am to 1 pm during vegetative, flowering and fruiting stages. Water productivity was calculated as the ratio of marketable fruit yield (kg ha^{-1}) and total water applied (m^3 ha^{-1}) (Patanè et al., 2011).

2.4. Fruit quality traits

Firmness (N) was measured by universal texture analyser (Shimadzu Make, Japan). Colour measurements were carried out using Hunter colorimeter (Model D25 Optical Sensor; Hunter Associates Lab Inc., Reston, VA, USA) on the basis of L*, a* and b*. The instrument (45°/0° geometry, 10° observer) was calibrated against a standard red coloured reference tile (L* = 25.94, a* = 28.98, b* = 11.97). The data reported are the average set of five determinations carried out on different berries each one consisting of four measurements on opposite points of the tomatoes. The colour index (CI) that may well describe the colour changes in the tomato fruits, was calculated following the equation (Intelmann et al., 2005): $CI = 2000\ a/[L(a^2 + b^2)^{(0.5)}$. The TSS was recorded using hand refractometer and the titrable acidity was determined by titrating against standard NaOH solution 0.1 mol/l until pH 8.1, using phenolphthalein as an indicator and expressed as anhydrous citric acid per 100 g (AOAC, 1990). Vitamin C (mg 100 g^{-1} FW as ascorbic acid) was determined by titration of homogenate tomato samples, diluted in a 3% metaphosphoric acid solution, using a 2,6 dichlorophenol indophenol dye solution standardized in a solution of ascorbic acid with a known concentration.

2.5. Statistical analyses

Data from the experiment were analysed statistically using SAS software (Ver. 9.3) in order to study the effect of withholding, DI and RDI on the yield and quality parameters of tomato and WUE. Pooled data was used for analyses as various parameters almost behaved similarly in their response to water stress on both the years. Duncan test and least significant difference (LSD) test were also performed for the comparison of means. The critical difference at $P = 0.05$ was used to test the difference between means of individual treatments.

3. Results

3.1. Fruit yield and water productivity

The fruit yield obtained under different irrigation levels for the two years is given in Table 3. The total (TFY) and marketable (MFY) fruit yield trends were similar but due to hot climate during the second year, the crop suffered a setback in terms of mortality of about one-fifth of transplanted seedlings. Though these were replaced, still the overall fruit yields were less. Considering the regulated deficit irrigation, the $RDI_{0.8}$ treatment did not impact the yield but MFY obtained with $RDI_{0.6}$ was about three-fourth of the full irrigation (FI, 1.0xETc). When the deficit irrigation ($DI_{0.6}$) was applied at different growth stages, it did not show any adverse impact during vegetative stage ($DI_{0.6VS;}$ 20–50 DAT), rather the yield improved by 4%. DI also showed little impact flowering ($DI_{0.6(FL);}$ 51–80 DAT) and a decline of 7% was monitored with DI during fruiting period ($DI_{0.6(FT);}$ 81–120 DAT). The DI applied for longer periods i.e. either of two stages ($DI_{0.6(VS+FL)}$; $DI_{0.6(FL+FT)}$; $DI_{0.6(VS+FT)}$) resulted in 14–18% reduction in MFY. The crop was able to tolerate interruptions of irrigation for 15 days i.e. simulating canal closures and the decline in yield was only 3–7%, the highest being at fruiting stages (II_{FT}).

The irrigation water applied plus rainfall (AW) during the two years averaged 464 mm under FI and the AW saved equalled 68 and 136 mm with $RDI_{0.8}$ and $RDI_{0.6}$, respectively (Table 2). Similarly with stage dependent DI, the water saved was 42–53 and 83–95 mm for single and combination of two growth stages, respectively while it was 49–57 mm for irrigation interruptions at different stages. Based upon the AW, the water productivity (WP) was calculated from marketable yield (Table 3). Highest WP of 19.1 kg m^{-3} was computed in $RDI_{0.8}$ and $RDI_{0.6VS}$ while lowest 16.8 kg m^{-3} was with full irrigation (FI) and $DI_{0.6(VS+FT)}$. WP for other treatments ranged between 17.5–18.5 kg m^{-3} water.

3.2. Growth, yield and physiological parameters

Growth parameters monitored in terms of plant height and LAI followed similar trend (Table 4). Though initially the maximum height and LAI were observed in case of $RDI_{0.8,}$ the final values of these parameters were the maximum with FI. $RDI_{0.6}$ and II_{VS} induced deeper rooting (~0.75 m) followed by $DI_{0.6VS}$ and II_{VS} (~0.65 m) while the minimum rooting depth (0.41 m) was observed in FI. Total root mass (26.7 g pl^{-1}) was also lowest in the latter. However, the leaves under FI and $RDI_{0.8}$ seemed to contain higher chlorophyll but the differences were non-significant.

Physiological parameters like photosynthetic assimilation rate (PAR), water vapour conductance (WVC), transpiration rate and intrinsic water use efficiency (iWUE) are presented in Fig. 1. These parameters remained almost similar under all irrigation treatments

Table 3
Fruit yield ($t\,ha^{-1}$) and water productivity ($kg\,m^{-3}$) under different deficit irrigation water strategies.

Irrigation schedules	Total fruit yield			Marketable fruit yield			Water productivity		
	1st yr	2nd yr	Mean	1st yr	2nd yr	Mean	1st yr	2nd yr	Mean
a) Regulated deficit irrigation									
0.6xETc [$RDI_{0.6}$]	71.9	59.2	65.5	66.7	50.7	58.7	20.5	15.3	17.9
0.8xETc [$RDI_{0.8}$]	88.3	78.0	83.1	84.8	67.2	76.0	21.5	16.9	19.2
1.0xETc [FI]	90.7	81.7	86.2	87.0	69.1	78.0	18.7	14.9	16.8
b) FI except DI (0.6xETc) at growth stage									
Vegetative [$DI_{0.6(VS)}$]	94.7	84.2	89.4	91.0	71.1	81.0	21.2	17.0	19.1
Flowering [$DI_{0.6(FL)}$]	89.1	78.8	83.9	84.2	67.9	76.0	20.2	15.9	18.1
Fruiting [$DI_{0.6(FT)}$]	86.4	71.8	79.1	81.2	65.6	73.4	19.9	15.8	17.8
Veg. & Flower [$DI_{0.6(VS+FL)}$]	77.6	63.4	70.5	72.7	56.4	64.5	19.0	14.8	16.9
Veg. & Fruiting [$DI_{0.6(VS+FT)}$]	80.7	69.5	75.1	76.2	57.5	66.8	20.5	15.6	18.0
Flow. & Fruiting [$DI_{0.6(FL+FT)}$]	77.7	64.8	71.3	72.4	56.5	64.5	20.1	14.9	17.5
c) FI except irrigation interrupted (15 d) during growth stage									
Vegetative [II_{VS}]	87.4	72.8	80.9	84.0	67.0	75.5	19.9	17.0	18.5
Flowering [II_{FL}]	86.5	72.8	79.6	81.2	63.3	72.3	19.9	15.4	17.7
Fruiting [II_{FT}]	88.1	75.4	81.7	83.9	66.2	75.1	20.7	15.6	18.1
LSD (p = 0.05)	5.2	4.8	5.2	5.3	4.2	4.8	1.2	1.1	1.1

Table 4
Growth parameters under different deficit irrigation water strategies.

Irrigation schedules	Height (cm)	LAI (90 DAT)			Root parameter		Chlorophyll ($mg\,g^{-1}$)		
		1st yr	2nd yr	Mean	Weight ($g\,pl^{-1}$)	Depth (cm)	1st yr	2nd yr	Mean
a) Regulated deficit irrigation									
0.6xETc [$RDI_{0.6}$]	83.7	2.50	1.98	2.24	33.8	75.1	2.81	2.87	2.84
0.8xETc [$RDI_{0.8}$]	84.1	3.51	2.98	3.25	29.4	50.1	2.97	3.21	3.09
1.0xETc [FI]	90.4	3.68	3.10	3.39	26.7	40.9	3.16	2.98	3.07
b) FI except DI (0.6xETc) at growth stage									
Vegetative [$DI_{0.6(VS)}$]	86.9	3.49	2.84	3.17	32.2	64.9	2.90	2.96	2.93
Flowering [$DI_{0.6(FL)}$]	85.8	3.14	2.56	2.85	31.1	55.0	3.04	2.98	3.01
Fruiting [$DI_{0.6(FT)}$]	83.3	3.48	2.76	3.12	29.9	50.7	2.88	3.06	2.97
Veg. & Flower [$DI_{0.6(VS+FL)}$]	83.3	2.94	2.45	2.70	34.6	69.1	2.82	3.00	2.91
Veg. & Fruiting [$DI_{0.6(VS+FT)}$]	84.6	3.25	2.61	2.93	33.1	59.9	2.92	2.86	2.89
Flow. & Fruiting [$DI_{0.6(FL+FT)}$]	81.2	2.80	2.26	2.53	31.9	63.5	2.97	2.79	2.88
c) FI except irrigation interrupted (15 d) during growth stage									
Vegetative [II_{VS}]	81.9	3.49	2.77	3.13	34.9	75.7	2.98	3.10	3.04
Flowering [II_{FL}]	80.1	3.17	2.63	2.90	32.6	65.8	2.73	2.89	2.81
Fruiting [II_{FT}]	85.3	3.40	2.70	3.05	31.1	50.7	2.96	3.08	3.02
LSD (p = 0.05)	0.6	5.2	4.8	5.2	5.3	8.8	NS	NS	NS

during vegetative stage while higher PAR, transpiration and WVC was monitored with FI during flowering and fruiting stages, followed by $DI_{0.6(FL)}$ and $RDI_{0.8}$. The iWUE was also higher during vegetative stages and declined with age especially during fruiting stage. However, the decline in iWUE was non-significant with $DI_{0.6(FL)}$ and $DI_{[0.6(VS+FL)]}$.

3.3. Fruit quality traits

The trends in fruit quality traits with different irrigation treatments were contrary to fruit yield except for fruit weight and its shape index (Table 5). Comparatively bigger sized fruits as indicated by higher weight (115–121 g) were monitored under FI, $RDI_{0.8}$, $DI_{0.6(VS)}$, II_{VS} while the fruit size was reduced considerably (77–81 g) under $RDI_{0.6}$, $DI_{0.6(VS+FL)}$, $DI_{0.6(FL+FT)}$ and II_{FT}. The shape index was also better with FI, $DI_{0.8}$, $DI_{0.6(VS)}$, and $DI_{0.6(VS+FT)}$. $RDI_{0.8}$ and $RDI_{0.6}$ as well as interruption of irrigation at fruiting (II_{FT}) induced firmness in fruits (N 3.4–3.6) while the fruits with FI were quite soft (N 1.9). Similar was the case with TSS, ascorbic acid and acidity where the values were higher (>5.0 brix; >200 ppm Ascorbic acid; >0.6% acidity) with $RDI_{0.8}$ and $RDI_{0.6}$. These parameters also got improved with $DI_{0.6FT}$ either alone or in combination with other growth stages. The DI at fruiting either with $RDI_{0.6}$ or $DI_{0.6(FT)}$ and $RDI_{0.6(FL+FT)}$ was observed to improve redness considerably (CI > 43) while the CI was lower (29–33) in case of FI and $RDI_{0.6(VS)}$ and II_{VS} (Table 5). The CI ranged between 37.2 and 39.6 under other irrigation treatments.

4. Discussion

Deficit irrigation in now considered as an option to minimise the irrigation water requirements and maximise water productivity in water scarce areas (Costa et al., 2007). The most of the vegetables including tomato being sensitive to water stress have largely been studied for deficit irrigation techniques (Kirda et al., 2004; Kuscu et al., 2014). The deficit irrigation has generally lead to lower yields of tomato (Topcu et al., 2007; Jensen et al., 2010) under stressed conditions, the yields were not even half of those with full irrigation (Patanè and Cosentino, 2010). In the present study, the regulated deficit irrigation though did not affect the yield at $RDI_{0.8}$, there was a loss of about one-fourth MFY with $RDI_{0.6}$ compared with the full irrigation (FI). Nevertheless the water productivity (19.2 $kg\,m^{-3}$) was the maximum under $RDI_{0.8}$. The potential of DI strategies to produce higher yields per unit of irrigation water applied has been highlighted by Costa et al. (2007); Fereres and Soriano (2007) but when the tomato was exposed beyond certain level of water stress,

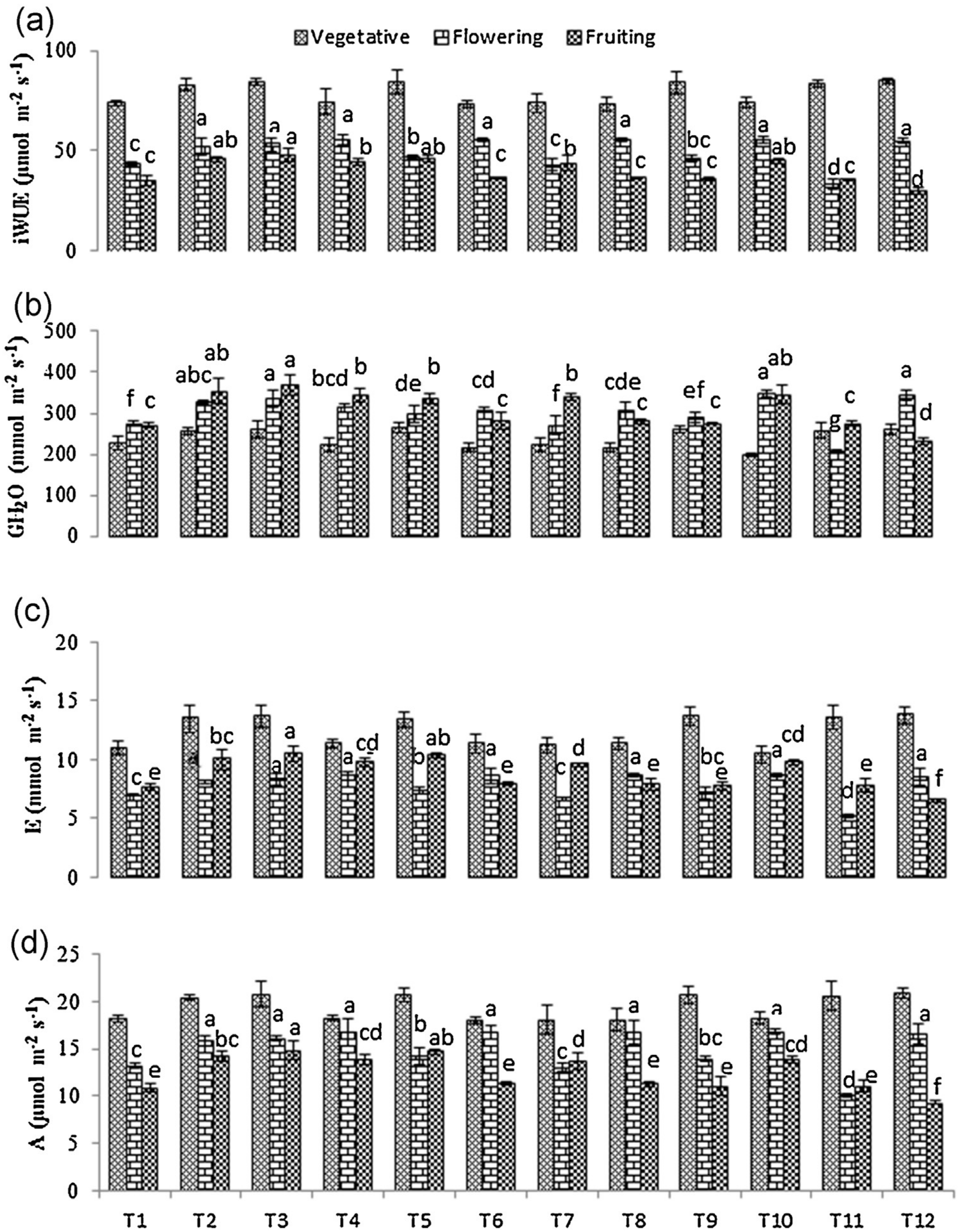

Fig. 1. Physiological parameters *viz*., intrinsic water use efficiency (a), water vapour conductance (b), transpiration rate (c) and assimilation rate (d) as influenced by water stress at different growth stages in tomato leaves.

it adversely affected MFY (Kirda et al., 2004; Kuscu et al., 2014). Moreover, all the crop growth stages are not equally sensitive to water stress. Thereby, to identify the critical stages where DI can be beneficial, it was tried at individual or combination of growth stages. Though the plants were exposed to water stress for longest duration (44 days) during vegetative stage, $DI_{0.6(VS)}$ was rather beneficial in terms of MFY and water productivity (WP). Compared to other treatments, this tended to enhance the rooting depth and weight (Table 4). Better root growth seems to have stimulated water and nutrient uptake from larger volume of soil and their transfer to vegetative portions. Further the sensitivity of tomato to water stress at flowering and fruiting has generally been attributed to floral abortions (Pulupol et al., 1996; Zegbe et al., 2006). However, this was not indicated from the number of fruits computed from MFY and fruit weight that was rather lower with FI. In fact, it was the underdevelopment of fruits as indicated by the fruit weight especially when DI was applied for longer durations e.g. $RDI_{0.6}$ and $RI_{0.6}$ at either two stages amongst vegetative, flowering and fruiting stages. Moreover, the undersized fruits were also more under these treatments. Some compensatory effect of revival of irrigation during fruiting was however noticed in terms of improvement in fruit size and MFY. Among the treatments where irrigation was interrupted for 15 days to simulate canal closure conditions, decline in MFY was more with $II_{FT.}$ This was obviously due to underdevelopment of fruits as indicated by fruit weight while II_{FL} resulted in floral abortion as was computed from number of fruits. The observation on the overall higher MFY obtained with DI and omission of irrigation during vegetative stage demonstrated the better tolerance of tomato. This is in consistent with earlier literature on tomato (Kuscu et al., 2014). Others (Zegbe et al., 2006; Gatta et al., 2007) have also reported the water stress to have more adverse impacts during flowering and fruiting stage. Some of the desirable attributes for marketing tomato include the fruit size, redness or lycopene, hardness and shape index while those for process-

Table 5
Quality parameters of tomato as affected by different deficit irrigation strategies.

Irrigation schedules	Firmness (N)	TSS (°Brix)	Asc. Acid (ppm)	Acidity(%)	Fruit wt. (g)	Shape index	Colour Index
a) Regulated deficit irrigation							
0.6xETc [$RDI_{0.6}$]	3.6	5.5	315	0.72	77.55	1.11	43.5
0.8xETc [$RDI_{0.8}$]	3.4	5.1	229	0.60	111.1	1.20	39.6
1.0xETc [FI]	1.9	3.4	175	0.44	118.9	1.19	29.1
b) FI except DI (0.6xETc) at growth stage							
Vegetative [$DI_{0.6(VS)}$]	2.8	4.2	187	0.45	115.1	1.21	33.0
Flower [$DI_{0.6(FL)}$]	2.2	5.1	197	0.52	99.3	1.20	35.0
Fruiting [$DI_{0.6(FT)}$]	2.2	5.3	258	0.59	92.5	1.16	43.2
Veg. & Flower [$DI_{0.6(VS+FL)}$]	2.4	4.4	217	0.48	80.3	1.14	38.4
Veg. & Fruiting [$DI_{0.6(VS+FT)}$]	2.1	5.1	257	0.62	89.5	1.21	39.9
Flow. & Fruiting [$DI_{0.6FL+FT}$]	2.0	5.4	267	0.64	80.9	1.09	44.3
c) FI except irrigation interrupted (15 d) during growth stage							
Vegetative [II_{VS}]	2.6	3.7	179	0.43	121.2	1.09	33.2
Flowering [II_{FL}]	2.7	4.3	208	0.47	104.9	1.12	37.2
Fruiting [II_{FT}]	3.4	4.8	201	0.44	80.7	1.07	38.7
LSD (p = 0.05)	0.2	0.6	14	0.03	13.5	0.06	4.04

ing are the total soluble solids, low fruit water content, ascorbic acid etc. Red colour in tomato is principally associated with the lycopene content and is generally considered the most important attribute determining the product quality (Hui et al., 2006). The quality parameters like hardness, TSS, ascorbic acid, acidity and colour were improved considerably with deficit irrigation. It has earlier been reported that transport of water may be reduced but not the photo-assimilates (Zegbe et al., 2006). The reduced fruit size and low dilution resulting from decreased water levels with in fruits must have resulted in accumulation of the assimilates thereby the improved the quality parameters. Similarly, other researchers have reported that the yield is inversely related to TSS and thus DI positively influences the quality parameters (Zegbe-Dominguez et al., 2003; Helyes et al., 2012; Kuscu et al., 2014). However, it would be of farmer's interest if the acceptable quality is improved without sacrificing the MFY. In the present study this could be achieved with $RDI_{0.8}$ and $DI_{0.6(VS)}$ where even the WP was maximum and this was followed by $DI_{0.6(FL)}$. The strategies of DI at other stages though improved the quality of tomato fruit but with the risks of losing MFY.

5. Conclusions

Keeping in view the producer's interests, the appropriate deficit irrigation should guarantee the sustainability of marketable fruit yield of tomato and also should have positive effects on fruit quality. Amongst the various options tried, this could be achieved with regulated deficit at 0.8xETc and stage dependent deficit irrigation (0.6xETc) during vegetative stage followed by flowering. The other option though improved fruit quality but not without scarifying the fruit yield. In case of scarcity of water, the most critical stage was flowering followed by fruit development.

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