Crop Res. **53** (1&2) : 88-96 (2018) DOI : 10.5958/2454-1761.2018.00014.1
With nine figures
Printed in India

Evaluation of the effect of irrigation timing on root zone soil temperature, moisture and yield of tomato

M. J. HASHEMPOUR[1], H. ANSARI[1,*] AND S. R. KHODASHENAS[1]

[1]*Department of Water Engineering*
Ferdowsi University of Mashhad, Mashhad, 9851, Iran
(e-mail : ansary@um.ac.ir)

(Received : December 12, 2017/Accepted : January 10, 2018)

ABSTRACT

This field experiment was conducted in order to evaluate the effects of day and night time irrigation (D_T, N_T) on tomato growth, yield and water use efficiency (WUE) at Meteorological Organization of Agricultural Faculty in Ferdowsi University of Mashhad, Iran. The investigation was carried out in three treatments and three replications in two irrigation timings, including one during the day and one at night on randomized plot design. Soil moisture, temperature and EC were measured at a distance of 30 cm from the drippers by data logger REC-P55. These parameters were recorded prior to and after irrigation. Irrigation was applied using tape drip system with drippers spaced every 30 cm. The discharge of the drippers was 2 l/h and the pressure was 0.5 bars. Drip tape instances in each block were considered to be 0.75 m. Three fixed irrigation regimes through the whole crop cycle in both D_T and N_T at I_1 (100%), I_2 (75%) and I_3 (50%) of the maximum irrigation water requirement (Iw) were used. The D_T water used volume by I_1, I_2 and I_3 was 17.2, 4.1 and 6.2% higher than the N_T correspondent volume, respectively. Tomato yield measured for D_T treatments was 7.88, 6.19 and 19.44 kg lower than N_T treatments. The results revealed that N_T treatments impression on tomato yield and WUE were not significant. Delivering irrigation at night may help reduce the water used volume and root-zone soil temperature, while increased water use efficiency up to 10% compared to D_T irrigation which may translate to improved plant growth. Proper irrigation timing together with efficient water management can help in obtaining a high amount of tomato yield.

Key words : Irrigation, moisture, soil temperature, tomato, WUE, yield

INTRODUCTION

Time of irrigation should be considered as a determinative factor in increasing crop yield per unit of water, especially in hot areas with limited water resources. The reduction in water and nutrients in soil can be the result of irrigation water deficit, which is the result of improper irrigation management in time (Wright, 2002). Research needs to be carried out on the effects of day and night water application timing on yield and water use efficiency (WUE). Higher growth and water use efficiency are the result of water applications during the day as compared to early morning applications (Warren and Bilderback, 2004; Davis *et al.,* 1985; Phene *et al.,* 1985).

Water applications during the day have practised widely only on sandy soils during the period that crop water used volume is high (Hartz, 1999). Nonetheless, night time irrigation may be required to decrease root-zone soil temperature and prevent plant water deficit and significant leaching of water and nutrients. Yeag *et al.* (1997) and Ismail *et al.* (2007) reported that early morning hours before 10 : 00 were the proper irrigation timing to reduce evaporation of irrigation water and to reduce the probability of winds blowing the irrigation water from the target region especially under sprinkler irrigation. Water spraying at dusk can also help in increasing the soil mass in the root zone area resulting in higher water absorption at night and in the morning (Ozawa, 1998). The interaction of soil temperature and water content will be needed to establish more efficient adaptation strategies to outweigh the impacts of greater temperature extreme events affiliated with a changing climate (Hatfield and Prueger, 2015). Dong *et al.* (2016) stated that night time irrigation was a proper adaptive strategy for farmers in hot areas. The objective of this study was to compare between day and night water application timings by evaluating their effects on crop production, soil moisture distribution and soil temperature and water use efficiency in tomato.

MATERIALS AND METHODS

An open field study 2014 evaluated the effects of day and night time irrigation (D_T, N_T) and fertilizer rate on tomato growth, yield and water use efficiency (WUE). The field experiment was laid out at Meteorological Organization of the Agricultural Faculty in Ferdowsi University of Mashhad. The land area was about 125 m^2. A well was considered to be an irrigation water supply to deliver well-water to experimental plots through polyethylene pipes. Prior to planting, triple soil samplings were collected and chemical and physical properties were determined at the soil at the water laboratory of college station. Details of analytic data are shown in Tables 1, 2 and 3.

Irrigation was applied using a tape drip system in which every block dimensions were 1.5 × 2.25 m^2. Each drip tape was placed at the surface of the soil with drippers spaced every 30 cm. The length of each drip tape was 1.5 m; the discharge of the drippers was 2 l/h and the pressure was 0.5 bars which were the same for all drippers. Drip tape instances in each block were considered to be 0.75 m. The detailed layout of the tape drip irrigation system is presented in Fig. 1.

The trial was carried out in three treatments and three replications in two irrigation timings, including one during the day and one at night on the randomized plot design. Soil water content, soil temperature and electrical conductivity (EC) were measured at a distance of 30 cm from the drippers. Soil water content was measured at 30 cm soil depth by a data logger REC-P55 (Fig. 2). Water content reflectometer sensors were installed vertically along 30 cm depth of soil for all

Fig. 1. Layout of drip irrigation network.

Fig. 2. Data logger REC-P55.

Table 1. The physical characteristics of the soil

Bulk density (g/cm^3)	PWP (%)	FC (%)	pH	Soil texture	Soil particles			Depth (cm)
					Clay	Silt	Sand	
1.35	18	36	7.7	Sandy-loam	31	31	38	0-30

Table 2. The chemical characteristics of the soil

Anion (meq/l)					Cation (meq/l)					SAR (%)	EC (dS/m)	O. C. (mg)	Depth (cm)
Total	SO_4^{-2}	HCO_3^-	Cl^-	CO_3^{2-}	Total	K^+	Na^+	Mg^{2+}	Ca^{2+}				
43.19	19.29	21.05	2.85	-	43.92	0.11	27.56	9.56	6.6	9.67	2.17	0.59	0-30

Table 3. The chemical characteristics of the irrigation water

Anion (meq/l)					Cation (meq/l)					SAR (%)	T. D. S. (mg/l)	EC (dS/m)	pH
Total	SO_4^{-2}	HCO_3^-	Cl^-	CO_3^{2-}	Total	K^+	Na^+	Mg^{2+}	Ca^{2+}				
22.39	7.39	9.38	5.6	-	22.83	0.06	12.17	5.3	5.3	5.29	1198	1.8	7.31

treatments. Soil water content, soil temperature and EC were recorded before and after irrigation. The tomato (*Lycopersicum esculentom* var. Mobile) seedlings were transplanted on 26 May. The row spacing was 0.75 m and in each plot area three rows were cultivated with plants spaced every 30 cm; therefore, 15 plants were tested. After three weeks from transplanting, the irrigation treatment timings were followed. For efficient irrigation scheduling, computation of crop-evapotranspiration (ETc) in different growth stages of a crop is indispensable.

The ETc can be measured either by using field water balance or by lysimeter (Prihar and Sandhu, 1987; Bandyopadhyay and Malick, 2003) or can be determined empirically by taking various standard methods into account (Doorenbos and Pruitt, 1977; Allen *et al.,* 1998; Pourmohammad and Alizadeh, 2014) with the help of crop-coefficient (Kc), and pan coefficient (Kp) values. As the lysimeter is not available, determination of Kp, Kc and ETc values using field water balance method was suggested, as both methods are based on water balance studies in root zone of plants (Prihar and Sandhu, 1987; Bandyopadhyay and Malick, 2003). Crop evapotranspiration was calculated using the following equation :

$$ETc=Kc \times Kp \times Ep \qquad ...(1)$$

Where, ETc=Maximum daily crop evapotranspirition in mm, Ep=Evaporation from a class A pan in mm, Kp= Pan coefficient with ranges between 0.6 and 0.9, Kc=Crop coefficient with ranges between 0.4 and 1.2 depending on growth stage.

Ep was measured in alternating time periods :

$$F=dn/ETc \qquad ...(2)$$

Where, F=Irrigation cycle and dn=Net water requirement.

The plant water requirement (Iw) was computed with the following equation :

$$Iw=dn/E \qquad ...(3)$$

Where, E=Efficiency of tape drip irrigation system (E=90%)

In all irrigation timings for each treatment, the supplied amount of water was not the same; irrigation started with 1.8 mm/day and gradually increased to 8.1 mm/day to cover the plant water requirements during each growing state. Phosphate and urea fertilizers were added twice, at 30th and 60th days of transplanting, at 10 cm below the soil surface in the root area of each plant. Irrigation timing and WUE were considered as the intended parameters to be compared. To investigate and evaluate the effects of these parameters in each treatment D_T and N_T at 50, 75 and 100% of Iw (I_1, I_2 and I_3), were conducted. Data were collected in total randomized blocks with three treatments and three replications. The investigated treatments and their abbreviations are stated in Table 4. The matured tomato appeared on 20 August, then, the harvesting season was started by collecting matured tomato once a week. For each plant, the fruit weight and numbers were recorded. The dry matter was analyzed by selecting three plants from each treatment at the end of the harvesting season. The weight of stem and leaves was evaluated for each plant dried at 70°C.

Table 4. Investigated treatments and their abbreviation

Treatments	Irrigation timings	I_W treatments (%)	Abbreviation
Day time	11 : 00-15 : 00 h	I_1=100 I_2=75 I_3=50	D_T
Night time	21 : 00-01.00 h	I_1=100 I_2=75 I_3=50	D_T

RESULTS AND DISCUSSION

Crop Yield

Fig. 3 shows the tomato yields for all investigated treatments. Water application in D_T was, rather than N_T (Fig. 6). D_T average tomato weight was 448.1 kg with 163.9, 146.7 and 137.4 kg for I_1, I_2 and I_3, respectively. Considering the N_T treatments, the average tomato yield was 461.4 kg obtained from I_1 (171.8), I_2 (152.9) and I_3 (136.8) kg. No significant differences were found between I_2 and I_3 treatments (Fig. 4A and 4B), but there was a significant difference between I_1 and the aforementioned treatments at $P \le 0.05$. The D_T treatments increased the maximum average tomato yield by 15.3% compared to N_T

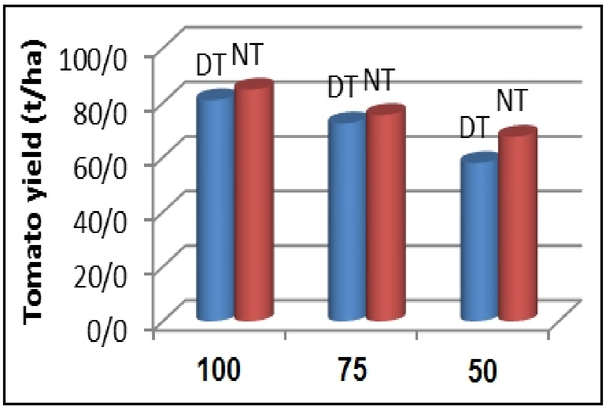

Fig. 3. Tomato yield for D_T *vs.* N_T treatments.

treatments. The most determinative factors which have a high influence on fruit weight, and number were the soil moisture and soil temperatures. Soil water content affected mainly the fruit weight, while the soil temperature affected mainly the fruit numbers; increasing soil temperature reduces fruit setting and consequently numbers (Ismail *et al.*, 2007). The high tomato yield (80.9 t/ha) of D_T treatments was due to the increase in fruit weight, while the high tomato yield (84.8 t/ha) for N_T treatments was the result of the increase in fruit number (Fig. 4).

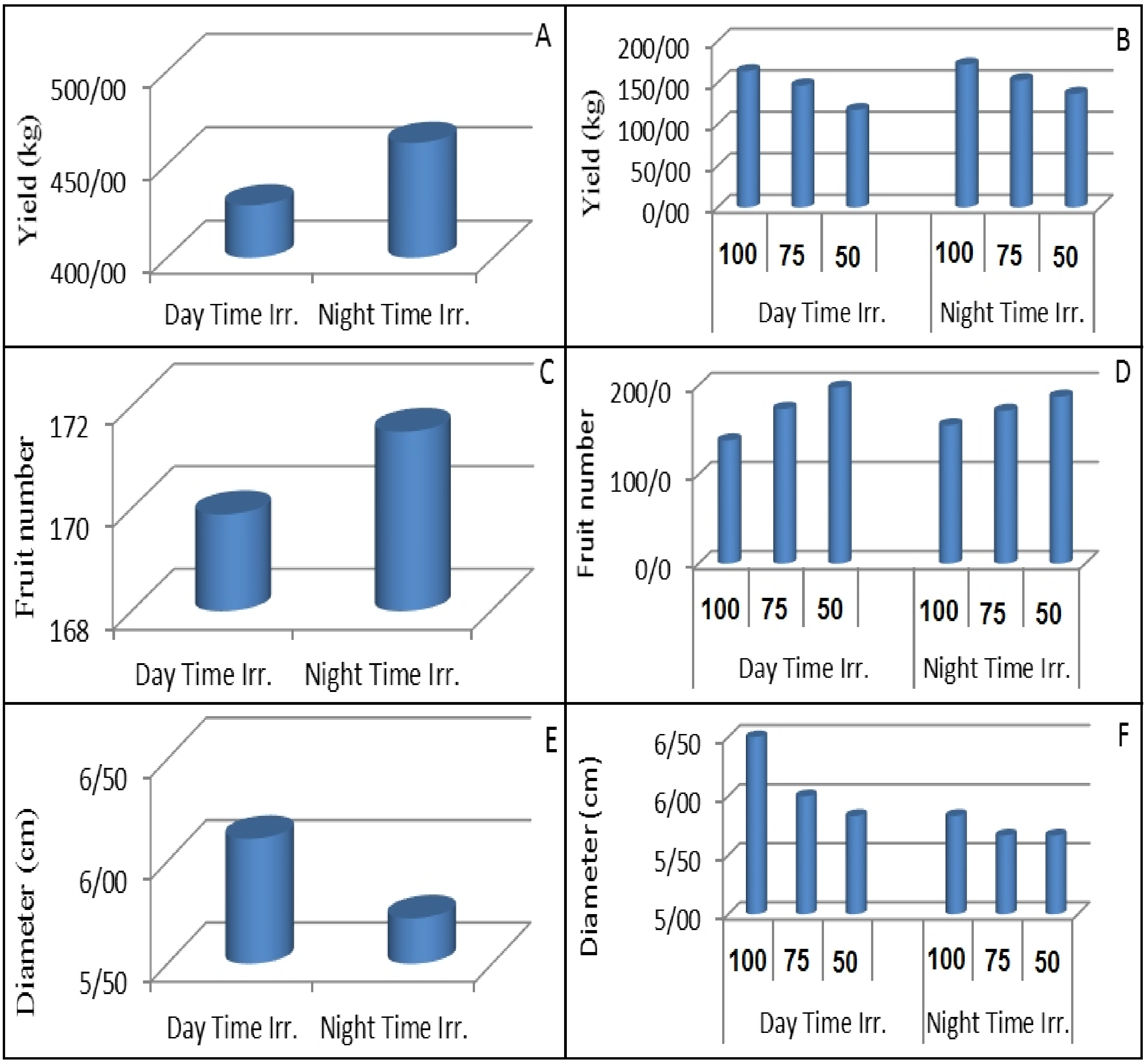

Fig. 4. Total average tomato yield for D_T *vs.* N_T (A), difference in total average tomato yield between irrigation treatments (B), the average fruit number for D_T *vs.* N_T (C), the difference between treatments in number (D), the average fruit diameter for D_T *vs.* N_T (E) and the difference between treatments in diameter (F).

Fruit Weight, Numbers and Diameters

The fruit weight, numbers and diameters are presented in Fig. 4. Significant differences in average fruit weight, numbers and diameters were found between treatments. The average fruit weight for D_T was higher than N_T treatments (Fig. 4A). The details of the exact difference between treatments are presented in Fig. 4B. The average fruit number recorded for N_T was greater than D_T treatments (Fig. 4C). The diversity between treatments is presented in Fig. 4D. The reduction in fruit diameter reported for N_T in comparison with D_T treatments was in line with the deceleration in fruit weight (Fig. 4E). The details of the reported differences are presented in Fig. 4F. As said previously, a reason for increasing the fruit weight is soil water content. The results of soil water content for D_T treatments (Fig. 5A) support that trend. It is anticipated that decrease in soil temperature at N_T treatments was associated with developing lower roots and depreciating less water leading to a higher fruit number and soil water content (Fig. 5A). The increase in fruit weight at D_T treatments was due to the increase in soil temperature and soil water content. The results of average soil temperatures among I_1, I_2 and I_3 treatments at 30 cm depth (Fig. 7) were inconsistent with the results of tomato yield between D_T and N_T treatments (Fig. 3).

Shoot Dry Matter

The shoot dry weight (stem and leaves) is presented in Table 5. The results indicated that there were significant differences in stem and leaf dry weights for all treatments at $P \leq 0.05$. The stem and leaves dry weight of D_TI_3 treatment was significantly less than the others. The highest leaves dry weight resulted from N_TI_1 treatments. The total shoot dry weight indicated that N_T irrigation produced the highest shoot dry weight. These results may be due to this that N_T irrigation had higher soil moisture compared to D_T irrigation (Fig. 5A).

Soil Water Content Distribution

The soil moisture or soil water content was measured prior to irrigation. Fig. 5A shows the average soil water content for D_T and N_T before and after irrigation. The distribution of soil water content at I_1, I_2 and I_3 for D_T and N_T treatments (at 30 cm depth) was presented too. For N_T treatments its average amount was 10.46% higher than D_T irrigation. For each D_T treatment (I_1, I_2 and I_3) the soil water content was less than the correspondent treatments at night, too (Fig. 5B). The distribution of soil water content can be divided into three stages (Fig. 8B). The first stage (May 26 to June 24) was during the first month after transplanting in which low soil water content was recorded for all irrigation timings. No deficit irrigation was applied during that stage to support faster root development, consequently at first 288 cm^3 of water was added manually and equally in all treatments. Later on deficit irrigation was implemented for both D_T and NT treatments. The second stage (June 25 to August 22) demonstrated a gradual increase in soil water content for all treatments and continued for two months. Throughout this stage, the water was applied by drip irrigation. The amount of

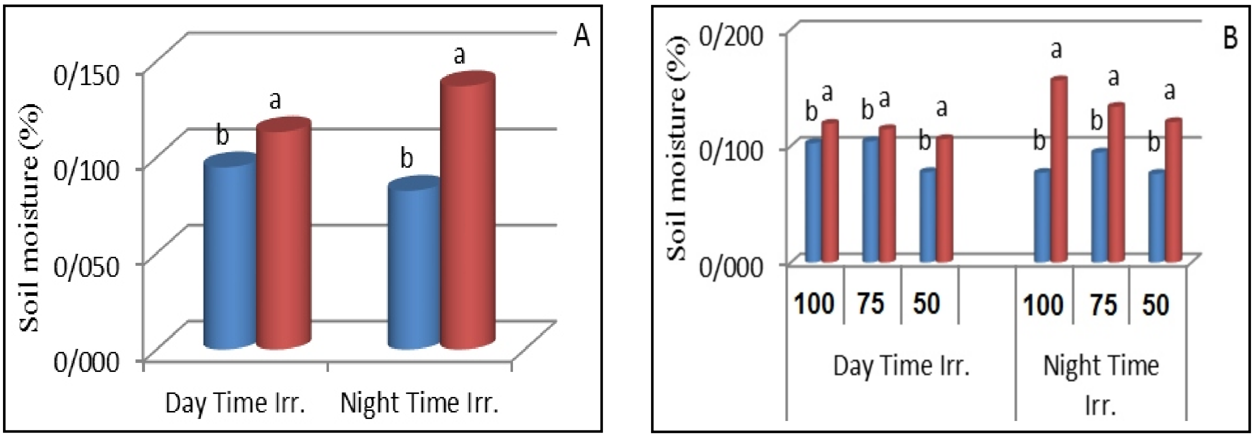

Fig. 5. The average soil moisture for D_T *vs.* N_T before (b) and after (a) irrigation (A) and the average moisture for D_T *vs.* N_T before (b) and after (a) irrigation (B).

Table 5. Water use efficiency for the Investigated treatments

Treatments	I_w treatments (%)	Average production (t/ha)	WUE (kg/m³)	Average fruit dia. (cm)	Average fruit weight (kg)	Average shoot dry weight (kg/plant)	Abbreviation
Day time	I_1=100	80.9	17.67	6.50	0.210	0.074	D_T
	I_2=75	72.4	24.82	6.00	0.156	0.069	
	I_3=50	57.9	28.18	5.83	0.114	0.066	
Night time	I_1=100	84.8	21.69	4.83	0.159	0.071	N_T
	I_2=75	75.5	26.91	4.67	0.153	0.068	
	I_3=50	67.5	34.89	4.67	0.135	0.064	
	LSD (P=0.05)		9.9				

applied water was gradually increased depending on the growth stages of the plants. After irrigation, the average soil water content for D_T treatments demonstrated a 16.6% reduction to N_T treatments. I_1, I_2 and I_3 showed a significant reduction in the soil water content, too (Fig. 5B). The water used volume, which had effects on soil moisture for both D_T and N_T treatments is shown in Fig. 6.

Soil Temperature

The results in Fig. 7A show the variations in average D_T and N_T soil temperature measured prior to and after irrigation. The details of the exact variations between treatments are presented in Fig. 7B; whilst, prior to and after irrigation, the difference in average soil temperature for D_T was small, it was sensible at N_T irrigation. Nonetheless N_T soil temperature transformation was lower than D_T before irrigation. After irrigation, the lowest soil temperature was obtained from N_TI_1, while the latter treatments showed significant differences. The highest average soil temperature was recorded for D_TI_1. After

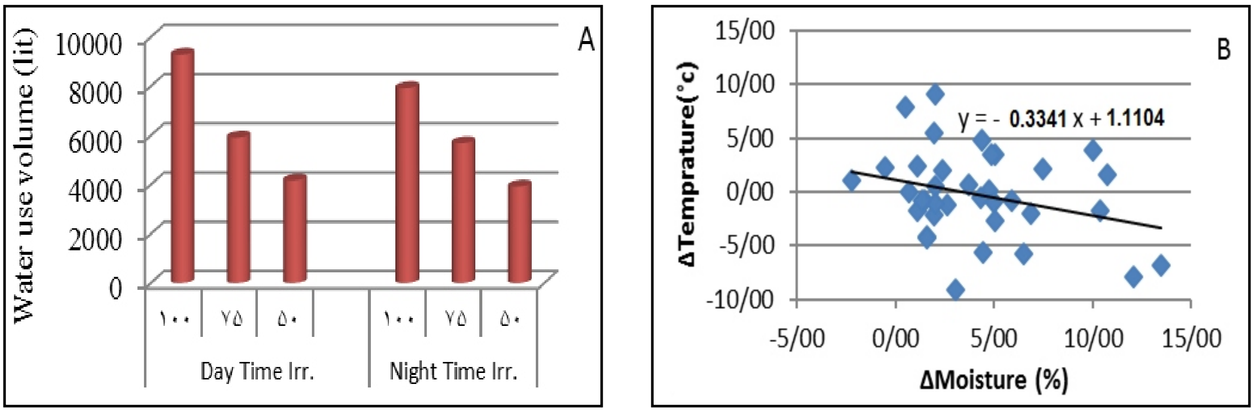

Fig. 6. The water used volume for D_T *vs.* N_T treatments (A) and the relation between soil temperature and moisture (B).

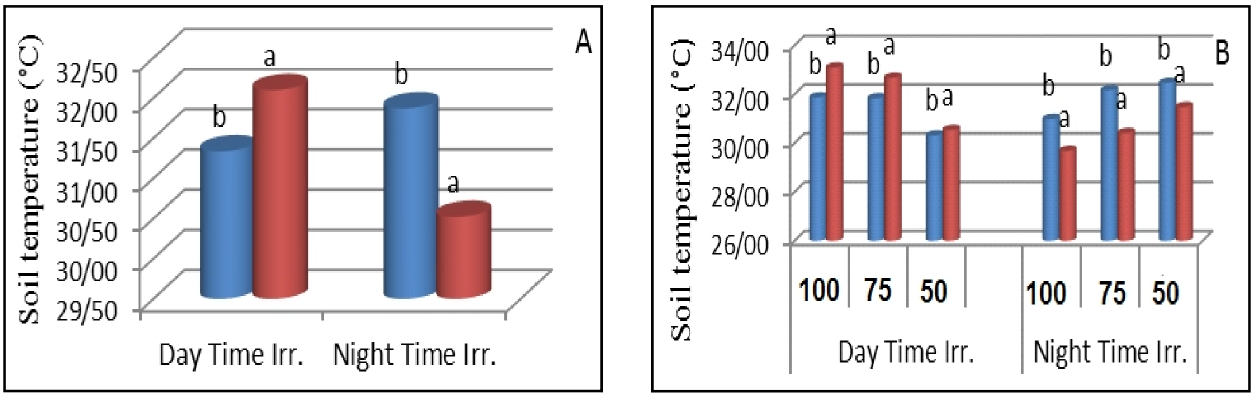

Fig. 7. The average soil temperature for D_T *vs.* N_T before (b) and after (a) irrigation (A) and the soil temperature for D_T *vs.* N_T treatments before (b) and after (a) irrigation (B).

irrigation, the decrease in N_T soil temperature was due to variations in soil thermal balance at different timings during the day. On the day, irrigation water transferred heat from the surface to the root zone, so the soil temperature at 30 cm depth was lower than the soil surface, while the reverse was true at night (Alizadeh, 2010). A comparison of soil temperature distribution along the soil depth and the soil moisture distribution revealed that the large increase in soil water content caused a small increase in soil temperature differences between D_T and N_T (Al-Kayssi *et al.,* 1990). As shown in Fig. 6B soil water content and soil temperature are interrelated. A 6.3% increase in the soil water content alternated the soil temperature about 1°C.This correlation would be related to the thermal diffusivity and thermal conductivity of sand content which formulated 38% of this soil. Both of these parameters were greater in wet sand than dry soil (Ismail *et al.,* 2007).

Variations in Average Soil Temperature and Moisture for D_T *vs.* N_T Treatments before and after Irrigation

Soil temperature showed an increase in these days during the D_T irrigation. The standard deviations (SD) of the soil temperature measured at 30 cm depth tended lower under N_T treatments, when soil temperatures measured at the depth of 30 cm were lower under N_T irrigation, when compared with D_T irrigation, as seen in the soil temperature time series in Figs. 8A and 8B. On 25 June, 2 July, 23 July and 31 July following N_T irrigation, soil temperature tended to decrease, as compared to no irrigation, while compared with the D_T treatments. Hitherto, a paired t-test (comparing N_T *vs.* D_T treatments) was done. The results showed that the reduction in the 30 cm soil temperatures due to N_T irrigation was not statistically significant for the events. A paired t-test on the average soil temperatures suggested that N_T irrigation reduced soil temperature by 0.31°C with a 95% confidence interval (0.32°C, 1.77°C) for the mean difference between D_T *vs.* N_T irrigated treatments. SD value in D_T treatments was larger than N_T treatments which could be related with the accelerated soil-air heat fluctuation in response to the application of water, when application of NT treatments reduced the soil temperature by less than the average 31.08°C. Average daily soil temperature during the 59 days from 25 June to 22 August was 30.3°C under N_T irrigation, compared to 31.8°C in the D_T irrigation regime. N_T irrigation cooling effect was related to the average daily soil temperature, and the larger extent of temperature reduction occurring on days when the soil was warmer. As shown in Fig. 8B, the soil temperature reduction due to N_T irrigation i. e. the difference between soil temperature in N_T and D_T treatments, resulting in 0.33°C reduction in 30 cm depth soil temperature for each 1°C increase in daily mean soil temperature. The median temperature of the well-water used for irrigation was usually at 20.5°C, ranging from 18.4°C to 23.6°C.

For irrigation management of the tomato crop, the applied water was measured by volumetric flow meters. During the period 25 June to 22 August, the soil moisture of N_T irrigation at a soil depth of 30 cm remained relatively moderate in an upward trend, while the soil water content for D_T irrigation was constant (Fig. 8C, D). The accumulated volumes of water applied from transplanting on 13 July and 31 July were 114 and 117 mm for the D_TI_1 treatment and 110 and 115 mm for the N_TI_1 treatment, respectively. The variation in soil water content as indicated in Fig. 8 was due to many factors. The high soil water content at the first stage of the growing season resulted from the large initial amount of water supply (288 cm^3 when required). During the second stage, the amount of applied water was also increased, due to the acceleration in infiltration rate and water retention in the soil profile. The reason for this phenomenon can be identified with the high demands of fruiting and evapotranspiration as a result of the hot weather of the growing stage. Furthermore, in 9-23 July the stability in the water supply at night time irrigation against the increased demand by plants led to much moisture deprivation from the soil profile inducing a reduction in soil water content. The more often the irrigation frequency, the higher the soil water content distribution.

Water Use Efficiency

Table 5 shows the WUE, which was represented by the production of yield in t/ha. The WUE was obtained from dividing the total

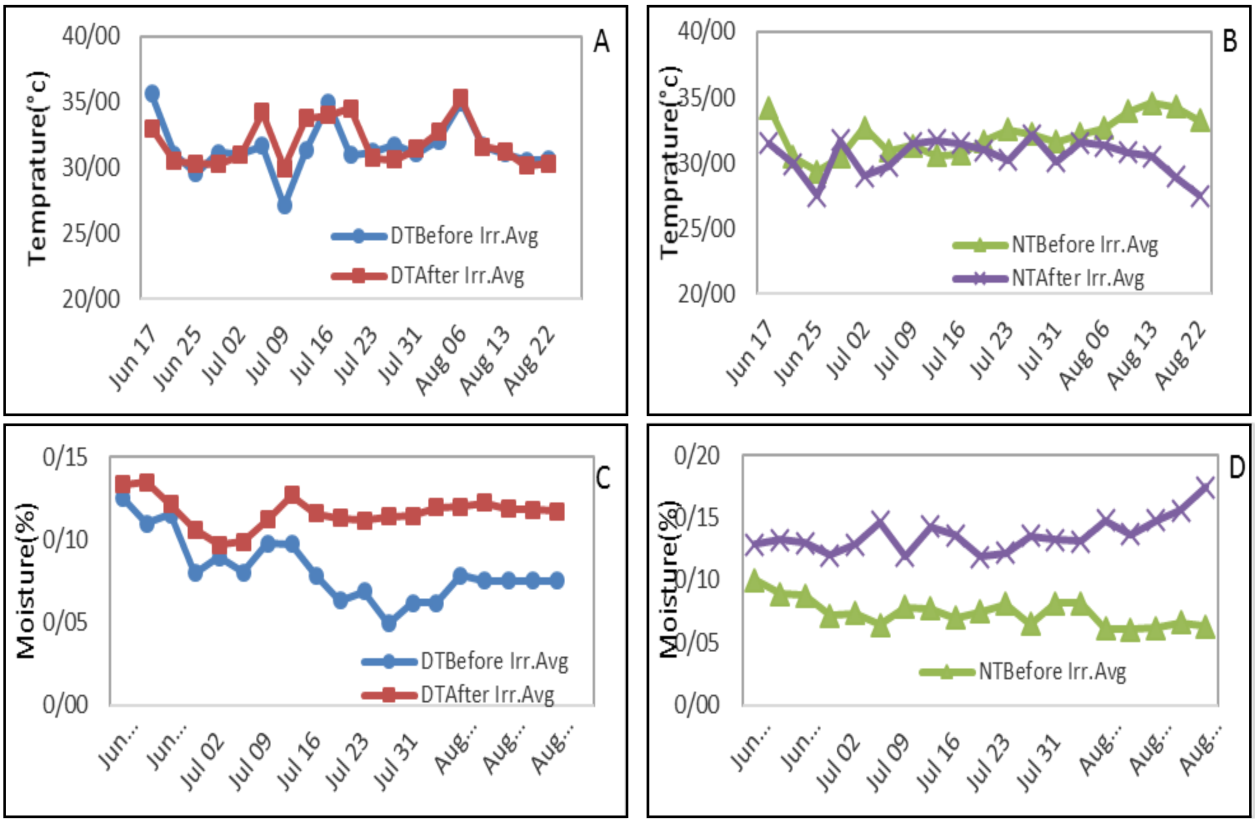

Fig. 8. Difference in average soil temperature for D_T *vs.* N_T treatments before and after irrigation (A and B), and difference in average soil moisture for D_T *vs.* N_T treatments before and after irrigation (C and D).

yield in kg/ha by the total water supply in m^3/ha. The water supply for D_T was 318.7 mm/ha, while for N_T was 288.5 mm/ha. The results indicated that no significant difference was found between D_T and N_T treatments. The highest water use efficiency obtained from N_TI_3 irrigation was because of the high amount of yield and low rate of water supply in this treatment (34.89 kg/m^3). This suggested that the N_T irrigation of water application increased mean water use efficiency by 8-23% compared to D_T irrigation. Although, daily periodical irrigation applied in a series of periods composed of irrigation and resting interval improved water use efficiency by 25-38% (Karam, 1993; Fare *et al.,* 1993; Tyler *et al.,* 1996). While plants yield increased with the increased water used volume; the decrease in the amount of water used within N_T irrigation didn't reduce tomato yield production significantly. Water used volumes during D_T irrigation of I_1, I_2 and I_3 were 17.2, 4.1 and 6.2% higher than N_T irrigation with plant yield differences of 7.8, 6.1 and 19.4 kg, respectively. The acceleration in tomato yield followed a permanent trend; D_TI_1, I_2 and I_3 were 4.58, 4.04

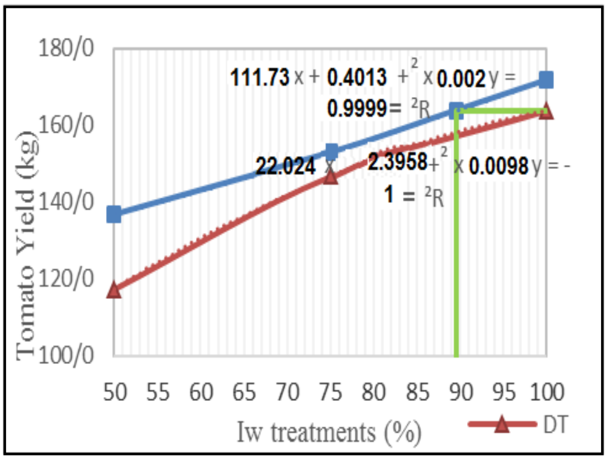

Fig. 9. Correlation between yield and Iw treatments in D_T *vs.* N_T.

and 14.2% lower than N_TI_1, I_2 and I_3. As shown in Fig. 9, the correlation between yield and Iw in both D_T and N_T treatments revealed that 89% of irrigation water requirement may have the highest rate of production and the lowest amount of water irrigation.

This study shows that, delivering irrigation at night through drip tapes may help reduce water used volume and increase root-zone soil temperature and water use efficiency up to 10% compared to day time irrigation, which may translate into improved plant growth and yield. Proper irrigation timing together with efficient water management can help in obtaining a high tomato yield.

REFERENCES

Alizadeh, A. (2010). *Soil, Water and Plant Relationship, 12th edn.* Imam Reza University, Mashhad.

Al-Kayssi, A., Al-Karaghouli, A., Hasson, A. and Beker, S. (1990). Influence of soil moisture content on soil temperature and heat storage under greenhouse conditions. *J. Agril. Engg. Res.* **45** : 241-52.

Allen, R. G., Pereira, L., Raes, D. and Smith, M. (1998). Crop evapotranspiration guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper No.* **56.** FAO, Rome, Italy.

Bandyopadhyay, P. and Malick, S. (2003). Actual evapotranspiration and crop coefficient of wheat (*Triticum aestivum* L.) under varying moisture levels of humid tropical canal command area. *Agric. Water Manage.* **59** : 239-54.

Davis, K., Phene, C., McCormick, R., Hutmacher, R. and Meek, D. (1985). Trickle irrigation frequency and installation depth effect on tomatoes. In : Proc. Third International Drip/Trickle Irrigation Congress, Fresno, CA. pp. 896-902.

Dong, Xu, Xu, W., Zhang, Y. and Leskovar, D. (2016). Effect of irrigation timing on root zone soil temperature, root growth and grain yield and chemical composition in corn. *Agronomy* **6** : 34-44.

Doorenbos, J. and Pruitt, W. (1977). Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper No.* **24** (revised), FAO, Rome.

Fare, D. C., Gilliam, C. G. and Keever, G. J. (1993). Monitoring irrigation at container nurseries. *Hortic. Technol.* **2** : 75-78.

Hartz, T. (1999). *Water Management in Drip-Irrigated Vegetable Production.* UC Davis, Vegetable Research and Information Center, University of California, Davis, CA.

Hatfield, J. and Prueger, J. (2015). Temperature extremes : Effect on plant growth and development. *Weather and Climate Extremes* **10** : 4-10.

Ismail, S., Ozawa, K. and Khondaker, N. (2007). Effect of irrigation frequency and timing on tomato yield, soil water dynamics and water use efficiency under drip irrigation. In : *Technology Conference, Vol. 1,* Sharm El-Sheikh (ed.). Egypt, March 15-18. pp. 69-84.

Karam, N. (1993). Overhead sprinkle strategies to reduce water and nitrogen loss from container-grown plants. Ph. D. dissertation. Virginia Polytechnic Institute and State University, Blacksburg.

Ozawa, K. (1998). Regulation of plant water and fertilizer absorption due to roots grown in sub-soil. *Bulletin No. 93.* Tohoku National Agricultural Experiment Station, Tohoku, Japan.

Phene, C., McCormick, R., Miymoto, J., Meek, D. and Davis, K. (1985). Evapotranspiration and crop coefficient of trickle-irrigated tomatoes. In : Proc. Third International Drip/Trickle Irrigation Congress, Fresno, CA. pp. 823-31.

Pourmohammad, Y. and Alizadeh, A. (2014). Using dual crop coefficient in estimating tomato water need on Mashhad climate. Iranian J. *Irriga. and Drainage* **8** : 1-15.

Prihar, S. and Sandhu, B. (1987). *Irrigation of Field Crops–Principles and Practices.* ICAR, New Delhi, India.

Tyler, H., Warren, S. and Bilderback, T. (1996). Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. *Environ. Hortic.* **14** : 194-98.

Warren, S. and Bilderback, T. (2004). Irrigation timing, effect on plant growth, photosynthesis, water use efficiency and substrate temperature. *ISHS Acta Horticulturae* **644.** International Symposium on Growing Media and Hydroponics.

Wright, J. (2002). *Irrigation Scheduling Checkbook Method.* Communication and Educational Technology Services, University of Minnesota, Minneapolis, MN, USA.

Yeag, T., Gilliam, C., Bilderback, T., Fare, D. C., Niemiera, A. X. and Tilt, K. M. (1997). *Best Management Practices Guide : Guide for Producing Nursery Crops.* United States Department of Agriculture Risk Management Agency.