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Water and radiation use-efficiencies of tomato (*Lycopersicum esculentum* L.) at three different planting densities in open field

Arazi koşullarında üç farklı bitki yoğunluğunda yetiştirilen domates'in (*Lycopersicum esculentum* L.) su ve radyasyon kullanım etkinliği

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ABSTRACT

An experiment was conducted to determine the simultaneous relationship between radiation interception, evapotranspiration, plant development and yield of Tomato (*Lycopersicum esculentum* L.) grown at three different planting densities: I_{100} (100x33 cm, 30 303 plant per hectare), I_{50} (50x33 cm, 60 000 plant per hectare) and I_{30} (30x33cm, 101 010 plant per hectare). Irrigation treatments were designed according to the wetted percentage in the field. The wetted area was 33% for I_{100}, 66% for I_{50}, and 55% for I_{30}. Comparing plant densities in terms of yield and plant development parameters, the findings indicated that a spacing of 50x33 cm was more suitable for tomato growth in fields at 60 000 plant per hectare since this interval probably provided cooler conditions at 30 cm in the soil profile, which also increased radiation use efficiency of the tomato. Hence, Radiation Utilization Efficiency in both fresh and dry weight (leaf+stem+fruit) was also higher with applied water of 950 mm and water consumption of 1263 mm in I_{50}. In the three plant densities, a combination of 60 000 plant per hectare (50x33 cm) gave the best planting intervals for tomato in terms of plant growth and yield.

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ÖZ

Bu çalışma, domates (*Lycopersicum esculentum* L.) bitkisinin su ve radyasyon kullanım etkinliğini, verim ve bitki gelişim parametrelerini aynı anda belirlemek için arazi koşullarında yürütülmüştür. Domates fideleri arazi koşullarına üç faklı sıklıkta dikilmiştir; I_{100} (100x33cm, 30 303 bitki hektar^{-1}), I_{50} (50x33cm, 60 000 bitki hektar^{-1}) ve I_{30} (30x33cm, 101 010 bitki hektar^{-1}). Sulama konuları ıslatılan alan yüzdesine göre oluşturulmuştur, I_{100} sulama konusunda alanın % 33'ü, I_{50} konusunda % 60 ve I_{30} konusunda alanın % 55'i ıslatılmıştır. Sulama konuları arasında verim ve bitki gelişim değerleri karşılaştırıldığında, bulgular 50x33 cm sıklığında dikilen veya bir hektar alanda 60 000 bitkinin olduğu bitki sıklığında en uygun sonucu vermiştir. Söz konusu bitki sıklığında (50x33cm) bitkilerin sağladığı gölgeleme ile toprağın ilk 30 cm derinliğinde daha serin bir ortam oluşturulmuş ve bu durum bitkilerin su ve radyasyondan daha etkili bir şekilde faydalanmalarını sağlamıştır. Domates bitkisinde hem yaş hem de kuru ağırlık olarak mevsimlik sulama suyunun 950 mm ve bitki su tüketiminin 1263 mm olduğu I_{50} konusunda elde edilmiştir. Bu nedenle, mevcut radyasyon ve uygulanan sulama suyundan en etkin bir şekilde faydalanılması için domates fidelerinin 50x33 cm aralığında dikilmesi sulama yönetiminde bir strateji olarak önerilebilir.

1. Introduction

Globally, environmental problems have increased in tandem with industrial development. Recently, some researchers have suggested that irrigation management could play a key role in sustainable agriculture by avoiding nitrate leaching, ground water pollution and excess water application. Furthermore, precipitations have varied year to year due to climate change. These circumstances exert significant stress on limited supply of water resources, especially during the irrigation season in summer. The tomato is quite sensitive to water deficit from flowering to yield formation (Doorenbos and Kassam 1979) and the amount of evapotranspiration varies according to climate conditions and growing techniques (Kodal et al. 1995).

Therefore, irrigation is required to achieve an economic yield, especially for crops sensitive to water deficit. A reduction in plant growth and yield because of water deficit has been well documented for tomato production (Kirda et al. 2004; Simsek et al. 2004).

Irrigation and fertilization are factors considerably related to the marketability of the product. Therefore, irrigation plays a key role in crop production. The quality of water and timing of irrigation affects primarily plant development and secondly the yield of plants (Yildirim 2010). Plant development depends on the amount of radiation, duration of light in a day, relative humidity, wind speed and temperature (Boztok 1990). The most effective development forces on plants are "Carbon", "Water", and "Radiation". Plant water, nutrient uptake and transpiration rate are closely related with solar radiation (Adams 1992). On crops, especially those grown in an open field, there is scarce data on the influence of regulated deficit irrigation and radiation use efficiency (RUE) (Sezen et al. 2006).

Research has so far not analyzed adequately the simultaneous relationship between different plant densities, solar radiation, radiation interception, evapotranspiration and yield of tomatoes. This study therefore examines these inter-related factors and their effects on plant development and tomato yield.

2. Materials and Methods

2.1. Experimental design and irrigation

The field experiment was carried out at the Dardanos Agricultural Research Station of Canakkale Onsekiz Mart University in Canakkale (Dardanelles), Turkey in the summer of 2012. The location of the experimental site was 40.08 ^{o}N, 28.20 ^{o}E at an altitude of 3 meters. The tomato seedlings (*Lycopersicum esculentum* L.) were transplanted on 5 May 2012 to the field in clay loam soils with 2.67% organic matter, pH of 7.07 and EC_e of 0.62 mS cm^{-1} at the site in three separate plots. Each plot was 10 m long and the row of the tomato plants were spaced 1.0 m (I_{100}), 0.5 m (I_{50}), and 0.3 m (I_{30}) apart, depending on the treatment. Spacing between plants in each row was a standard of 0.33 m. Drip tape with emitters spaced 33 cm apart and a discharge of 4 L h^{-1} were placed in the plant rows. Yildirim (1996) reported that if spacing between plant rows is greater than the spacing between emitters on the drip tube, typically a single tube should be used per row of plants. In the reverse situation, one tube should be used in the center between two rows of plants. Accordingly, in the experiment one drip tube for each plant row was used for the treatments I_{100} and I_{50}, but one drip line was used in the center between the two rows in the I_{30} treatment. The layout of the experiment is given in Fig. 1.

The electrical conductivity of the irrigation water (EC_w), measured with an EC59 pyranometer (Milwaukee Instruments, Inc.) was 0.410 ds m^{-1}. The experiment was laid out using a randomized complete block design with 3 replications. Each replicate in the I_{100} and I_{50} treatments included 40 plants while there were 80 plants in the I_{30} treatment. Climate parameters (solar radiation (W m^{-2}), temperature (^{o}C), relative humidity (%)) at the site were measured 1.5 m above the canopy of the plants using a HOBO U12 data logger (MicroDAQ.com Inc.). All data were measured by the HOBO U12 sensors and saved in the data logger at 1-hour intervals throughout the experiment for the whole growing season.

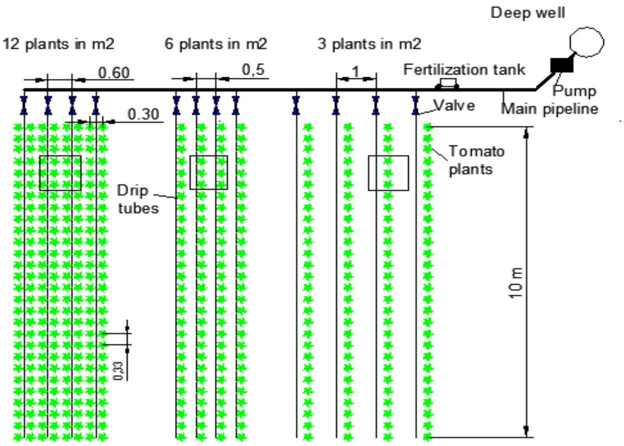

Figure 1. Layout of experiment and drip lines in three treatments.

2.2. Irrigation and fertigation

Each plot in all treatments took the same recommended amount of fertilizer; 128 kg ha^{-1} (NPK; 18:18:18) applied three times. Tomato is very sensitive to water deficit (Doorenbos and Kassam 1979). For this reason, the full water requirement of the plants was applied to all treatments and water was refilled in the root zone up to field capacity. However, the percentage of wetted area created different irrigation treatments since the plants had different row spacings. Available soil moisture for each depth of 30 cm from 0 to 90 cm was determined gravimetrically and the amount of irrigation water to be applied was calculated based on Gungor et al. (1996), which increased available soil moisture up to field capacity:

$$d = (((FC-ASW)/100).\gamma_s.D).P$$

where d= depth of water to be applied to the field (mm), FC= field capacity (%), ASW= available soil moisture, γ_s = soil bulk density (g cm^{-3}), D= required depth to be refilled up to field capacity (mm), P= percentage of wetted area (%), calculated as below:

$$P = 100.(S_d/S_l)$$

where S_d = space between drippers on the drip tube, and S_l= space between drip lines. The percentage of wetted area was 33% for I_{100}, 66% for I_{50}, and 55% for I_{30}. The experimental treatments included three irrigation regimes created by different wetted areas by placing drip lines between plant rows.

Evapotranspiration (ET) was calculated with the water balance equation given below:

$$ET = I + P + C_r - D_p - R_f \pm \Delta SW$$

where ET is evapotranspiration (mm), I is the amount of irrigation water (mm), P is rainfall (mm), and ΔSW is the change in soil water content (mm) determined gravimetrically. In the equation, Capillary rise (C_r), Deep percolation (D_p) and Runoff (R_f) were ignored since soil moisture in all treatments was increased up to the field capacity.

Water use efficiency (WUE) (kg m^{-3}) was defined according to Tanner and Sinclair (1983):

$$WUE = Y / ET$$

where Y is yield (kg ha^{-1}), and ET is evapotranspiration (mm).

2.3. Radiation and radiation use efficiency

The pyranometer (Hobo U12) was placed in the middle row and above a reference plant at a height of about 1.5 m and connected to the data logger processer input to measure total solar radiation (W m^{-2}) as registered time and date at 1-hour intervals. Daily solar radiation was estimated as MJ m^{-2}, as recommended by Monteith (1977). An exponential function was used to estimate intercepted radiation (F) using LAI (Monteith and Elston 1983; Trapani et al. 1992).

$$F = 1 - \exp(-k\ LAI)$$

where the extinction coefficient (k) for total solar radiation is equal to 0.7 (Sarlikioti et al. 2011). The PAR (Photosynthetically Active Radiation) (Si) was assumed to be equal to half of the total incident radiation (Monteith and Unsworth 1973). Multiplying the intercepted radiation with PAR gives an estimate of the amount of radiation intercepted by a crop canopy (IPAR). The radiation utilization efficiency (RUE) for total dry matter (RUE_{TDM}) and for total yield of tomato (RUE_Y) were calculated as defined by Ahmad et al. (2008).

$$IPAR = F \cdot Si$$

$$RUE_{TDM} = TDM / \sum IPAR$$

$$RUE_Y = Y / \sum IPAR$$

where TDM is total dry matter (leaves, stem, fruit) (g $plant^{-1}$), and IPAR is the intercepted radiation by a crop canopy (MJ m^{-2}).

2.4. Growing degree days (GDD)

GDD was calculated to evaluate the effect of temperature on plant growth. Daily minimum and maximum air temperatures were recorded by the weather station at the experimental site. The daily GDD was calculated using the standard formula given by Sadek et al. (2013):

$$GDD = [(T_{max}+T_{min})/2-T_{base}]$$

where T_{max} and T_{min} are the daily maximum and minimum air temperatures. T_{base} is the base temperature for tomatoes; below this, little plant growth occurs, so that T_{base} is required for GDD. Colado and Portas (1987) used three different base temperatures of 6 °C, 8 °C, and 10 °C for processing tomatoes in three different locations for different growing cycles. Therefore, the base temperature, considering the growing cycle and climate for processing tomatoes, was taken as 7 °C at our site.

2.5. Relative turgidity

Leaf water content was calculated from Thomas et al. (1971):

$$RT = [(FW-DW)/(TW-DW)]x100$$

where RT = relative turgidity, FW = field weight, TW = turgid weight and DW = dry weight (dried at 70°C in the oven). Leaf relative water content (LRWC) was determined at each sampling date. Four leaves per plant from each treatment were randomly collected to minimize age effect, as recommended by Kırnak and Kaya (2004).

3. Results and Discussions

Irrigation was initiated on 5 May 2012 and a similar irrigation volume of 30.7 mm was applied to all treatments in May to establish plant development. In June 2012, irrigation treatments commenced, as shown in Fig. 2. The amount of irrigation water fluctuated depending on plant density. Therefore, the volume of irrigation was, from highest to lowest, I_{50} (950 mm) > I_{30} (788 mm) > I_{100} (470 mm). The values of irrigation water per month were the highest in the I_{50} treatment. The highest amount of irrigation water was observed from the combination of 50x33 cm with a single drip line, since it had the highst wetted area (66%).

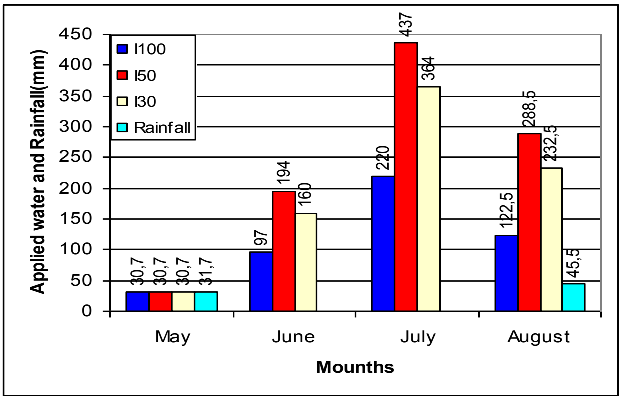

Figure 2. Amount of irrigation water applied and rainfall per month (2012).

A similar trend was observed for evapotranspiration, being 1263 mm for $I_{50,}$ 1101 mm for I_{30}, and 786 mm for I_{100} (Table 1). According to ANOVA, the treatments had a significant effect on yield. While the lowest yield was obtained from I_{100}, the highest was from I_{50} and $I_{30,}$ because plants in the I_{100} treatment had the lowest wetted area (33%). The yield, even though there were no statistical differences, was slightly higher in I_{30} rather than I_{50} since the treatment of I_{30} included 12 plants m^{-2}. Due to this, it produced a slightly higher yield than the I_{50} treatment with 6 plants m^{-2}. Therefore, having a double plant density in I_{30} does not mean a twofold increase in yield; and this also reduced marketable fruit quality. Even though the differences in WUE values were not significant, they were slightly higher in I_{30}, and, in turn, I_{50} and I_{100}.

Table 1. Applied water (mm), ET (mm), yield (kg ha^{-1}), mean number of fruits and weight per plant per treatment.

Treatment	Applied water (mm)	ET (mm)	Yield** (kg ha^{-1})	Mean number of fruits** per plant	Mean fruit weight $^{(ns)}$ (g)	WUE (kg m^{-3})
.	470.4	786.8	57540^b	69^c	83	7.31
I_{50}	950.4	1263.5	93200^a	108^b	86	7.38
I_{30}	788.1	1101.6	95260^a	136^a	70	8.65

*Probability level 5% (p<0.05), **Probability level 1% (p<0.01), ns: not significant.

Fruit weight and size decreased as plant density increased. Therefore, increasing the plant density of tomatoes does not mean improving the efficiency of the tomato yield to any worthwhile degree. Law-Ogbomo and Egharevba (2009) reported that the highest yield per hectare was obtained from the combination of seedlings transplanted in a spacing of 30x60 cm. Considering the physiology of the tomato, spacing between rows should be at least 50 cm to achieve maximum marketable fruit yield. Different treatments had a significant effect on the number of fruit per plant; however, there was no significant effect on the mean fruit weight. The total number of fruit per plant, contrary to the results found by Law-Ogbomo and Egharevba (2009), increased as planting density increased in I_{30}, but the average weight of fruit decreased (Table 1). Hence, to increase marketable yield, planting spaces between the plants and within rows should be at least 50 cm and 33 cm, respectively, that is, there should be 6 plants m^{-2}. In the present study, the highest marketable tomato yield was recorded as 95260 kg ha^{-1}, treated with 128 kg N ha^{-1} at a spacing of 30x33cm, in which, however, plant density was double compared to I_{50}. The best performance of the crop was observed from the I_{50} treatment, probably due to there being less competition between plants.

The growing period of tomato (*Lycopersicum esculentum* cv.) lasted 120 days after transplanting. During this period, GDD accumulation at the experimental site, located in a semi-arid region, was 2182 GDD's above 7 ^{o}C. Therefore, tomatoes require at least 2182 ^{o}C in a growing season to ripen.

Leaf area decreased in all treatments after completing the entire experiment, especially 80 days after transplanting (80 DAT) due to acceleration of plant physiology and leaf senescence. The reduction in LAI (Leaf Area Index) in the I_{100} treatment resulted in a reduction in the amount of intercepted PAR, which also decreased biomass as fresh and dry weight (Table 2). Leaf and stem development in the I_{100} treatment were good, but plants could not convert radiation and water into an economic yield compared with I_{50} and I_{30}. On the other hand, even though plant development parameters such as leaves and stems in the I_{30} treatment were low, the treatment produced a high yield by using radiation and water efficiently (Table 1).

Leaf area index (LAI) of the tomato varied with differing plant densities, especially after full bloom (35 DAT). In the leaf area, significant differences appeared between treatments. While I_{50} treatment was in the first group, the treatments of I_{100} and I_{30} were in the second group. The maximum value of LAI was recorded as 7.3 in I_{50} and LAI values were very close in the treatments of I_{30} and I_{100} as 3.3 and 3.2, respectively. Having a higher wetted area (66%), I_{50} may have provided plants with better development towards the end of the growing season. Lindquist et al. (2005) reported that a reduction in LAI resulted in reduced PAR interception and contributed to consistently lower biomass. Hence, crop biomass production is related to the amount of photosynthetically active radiation intercepted by the leaves. Low values of LAI in the I_{100} may be attributed to plant spacing, since large intervals between plants increased evaporation rather than transpiration due to less shading from other plants. ANOVA results for the plant development parameters; plant height and diameter were F= 1.6680, P= 0.248 (ns), DF= 4, F= 1.376, P= 0.306 (ns), and DF= 4, respectively. For these parameters, the wetted percentage indicated similar trends. However, plant growth decreased in the higher plant densities (Table 3), possibly owing to heavy shading. Current results agree well with Yoshioka and Takahashi (1979).

Even though the differences in leaf relative water content (LRWC) are not statistically significant (F= 1.13, P= 0.408 (ns), DF= 2), LRWC decreased from I_{100} to I_{30} (Table 4). Plants in the I_{100} treatment maintained their turgor pressure but development parameters and yield were low. On the other hand, LRWC in the I_{30} treatment was low, the reason probably being competition between plants. Therefore, leaf water potential is not a good indicator in identifying whether plants are under stress or not, which is supported by Ngouajio et al. (2006). Rudich et al. (1981) also indicates that atmospheric factors had a more significant effect on leaf water potential for tomatoes rather than soil water availability.

Density of plants for the tomato affected the amount of intercepted PAR (IPAR), which was the highest for each month in the I_{50} treatment (Fig. 3). During the whole growing season (5 May-15 September 2012), the total amount of solar radiation was 3144 MJ m^{-2} and IPAR decreased with the reduction of LAI; values were 758 MJ m^{-2} for I_{100}, 1073 MJ m^{-2} for I_{50}, and 1009 MJ m^{-2} for I_{30}. Although plants in all treatments were exposed to the same radiation, the amount of IPAR differed significantly. The highest IPAR was observed in the order of I_{50}> I_{30}> I_{100}. The reason for this was mainly leaf area, since IPAR was estimated by leaf area. The planting pattern also had a significant effect on RUE regarding fresh and dry weight and also IPAR, being (F= 7.976, P= 0.0012<0.05, DF=4,) for I_{50}, (F= 8.337, P= 0.011<0.05, DF= 4,) for I_{30}, and (F= 90.6, P= 0.001<0.01, DF =4) for I_{100}, respectively. Hence, plant density and wetted percentage in the field had a considerable effect, firstly on plant development, and secondly on yield; such that the effect of plant density was equally as important as regular irrigation.

RUE altered significantly according to plant density (Table 5), based on fresh and dry weight values of 2.74 and 0.42 g MJ^{-1} for I_{100}, 1.90 and 0.22 g MJ^{-1} for I_{50}, and 1.70 and 0.19 g MJ^{-1} for I_{30}. Even though RUE was higher for both fresh and dry weight, with a water consumption of 786 mm in I_{100}, the plants could not convert radiant energy (PAR) into chemical energy.

Table 2. Fresh and dry weight of leaves, stem and fruits.

	I_{100}						I_{50}						I_{30}					
	Leaves g $plant^{-1}$		Stem g $plant^{-1}$		Fruit g $plant^{-1}$		Leaves g $plant^{-1}$		Stem g $plant^{-1}$		Fruit g $plant^{-1}$		Leaves g $plant^{-1}$		Stem g $plant^{-1}$		Fruit g $plant^{-1}$	
Date (2012)	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight
16.05	1.49	0.15	0.67	0.08			1.49	0.15	0.67	0.08			1.49	0.15	0.67	0.08		
05.06	10.42	1.49	10.29	1.35			17.56	2.29	15.63	1.87			10.45	1.58	7.27	0.93		
19.06	68.01	11.06	78.40	9.15			88.10	14.13	121.87	14.55			32.28	6.45	49.01	6.70		
17.07	331	55.43	322	50.60	348	21.91	330	53.7	311	48.80	263	15.7	63.60	11.50	81.20	14.30	569.6	36.1
08.08	440.20	75.25	439	92.50	380	23.20	301	49.06	367	72	771	47.1	76.80	13.70	89.20	17.30	922.7	55.8
27.08	297.20	72.48	755.50	199.60	447	28	261.30	66.50	539	126.80	867	56.8	141	25.60	304.10	64.10	943.1	61.3

Table 3. Plant development parameters.

	I_{100}			I_{50}			I_{30}		
Date (2012)	Plant height (cm)	*Diameter	Leaf number	Plant height (cm)	*Diameter	Leaf number	Plant height(cm)	*Diameter	Leaf number
16.05	14	3	6	14	3	6	14	3	6
19.06	38	33	284	43	36	330	41	29	165
17.07	70	73	1138	55	54	1075	61	42	368
08.08	77	55	110	65	65	840	58	45	431
27.08	85	65	Senes	85	55	Senes	80	53	Senes

*Diameter is average of two directions; X and Y, Senes = senescence

Figure 3. Solar radiation, IPAR and GDD.

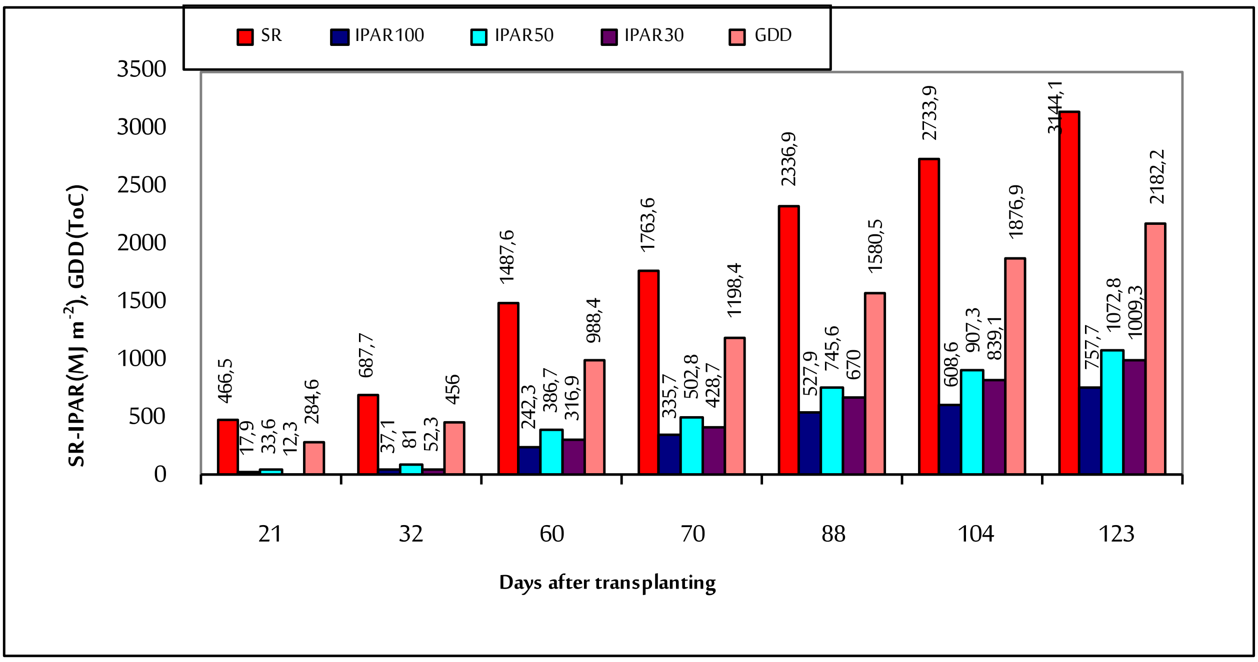

Table 4. Leaf relative water content (LRWC).

Date (2012)	Leaf Relative Water Content LRWC (%)		
	I_{100}	I_{50}	I_{30}
05.06	67.34	58.67	51.43
19.06	80.49	75.51	81.08
17.07	75.00	78.26	71.05
Average	74.28$^{(ns)}$	70.81$^{(ns)}$	67.85$^{(ns)}$

ns: not significant

Table 5. Radiation use efficiencies as fresh and dry weight.

Date (2012)	*$RUE_{fresh\ weight}$ (g MJ^{-1})			*RUE_{TDM} (g MJ^{-1})		
	I_{100}	I_{50}	I_{30}	I_{100}	I_{50}	I_{30}
05.06	1.16	0.99	1.45	0.16	0.12	0.20
19.06	2.90	1.96	1.12	0.40	0.27	0.18
17.07	3.71	2.15	2.04	0.47	0.28	0.18
08.08	2.81	2.18	1.84	0.43	0.25	0.15
27.08	3.14	2.24	2.04	0.63	0.20	0.22
Average	2.74^{a}	1.90^{b}	1.70^{c}	0.42^{a}	0.22^{b}	0.19^{b}

*Probability level 5% ($p<0.05$)

These results confirm that RUE was significantly dependent on crop water consumption, and also plant density. Machado et al. (2003) reported that the root density of tomato was concentrated in the first 40 cm in the soil profile. Zotarelli et al. (2009) reported that tomato roots were concentrated in the upper 15 cm in the soil profile, especially in the vicinity of the surface drip irrigation line. Gungor et al. (1996) stated that evaporation in the first 30 cm in the soil profile occurs more intensively than transpiration. In present study, although proper irrigation management was carried out in all applications, plant development and also yield were low in I_{100}, which may be attributed to water stress, since less shading by other plants increased evapotranspiration in the first 30 cm of the soil profile throughout the whole growing season. Therefore, large intervals between plants put tomato plants under intense stress because of reduced shade, which increases evaporation throughout the first 30 cm soil layer even when plants have completed their full development stage.

The amount of solar radiation intercepted by plants is a major determinant of the total dry matter produced by a crop (Biscoe and Gallagher 1978). Dry matter per plant (including leaves, stem and fruit) was the highest in I_{100} (300 g plant $^{-1}$), followed by I_{50} (250 g plant $^{-1}$), and I_{30} (151 g plant $^{-1}$), as shown in Table 2. These results may be attributed to the effect of plant density, since evaporation through the entire growing season was high, and the wetted percentage in I_{100} was lower than I_{50} and I_{30}. Total dry matter production per hectare was the highest for the highest plant density, even though dry matter production per plant was the highest in I_{100}, having the lowest plant density.

Plant development parameters in terms of plant height and diameter were not influenced by plant density but leaf number was the highest in I_{100}, despite having low LAI. RUE increased for tomatoes during the fruit development stage. This finding is supported by Gimenez et al. (1994) and Whitfield et al. (1989), who underlined that RUE increases for sunflowers after increasing respiratory load at the grain filling stage. IPAR for the tomato decreased with reduction in LAI since leaf development reported in the literature is the efficiency of conversion of radiant energy (PAR) into chemical energy through photosynthesis, affecting plant growth. Hence, leaf area expansion is affected significantly by water stress, as stated in the literature. In the present study, tomatoes planted at wide intervals in I_{100} were under more stress than the plants in other treatments. For plant spacing at 50x33 cm, in other words, 6 plants m^{-2} may be a good choice for tomatoes since each plant receives a better share of moisture and nutrients in the root zone. To decrease plant density to 3 plants m^{-2} (I_{100}) was not a good choice for tomato production. On the other hand, increasing plant density to 12 plants m^{-2} (I_{30}) did not lead to an increase in fruit yield much higher than the I_{50} treatment. Therefore, the best treatment combination for optimum yield of tomato was 60 000 pph. These findings agree well with Law-Ogbomo and Egharevba (2009) recommended combination of 55 555 tomatoes per hectare treated with 400 kg NPK ha^{-1}. Patane et al. (2010) recommended that tomato plant density at 5 plants m^{-2} may be beneficial for processing tomatoes in semi-arid environments.

4. Conclusions

Irrigation is the most important factor in increasing crop yield; however, plant density in an open field also plays a critical role in increasing yield since the response of plant physiology to different environments and water levels can vary. Yavuz et al. (2007) obtained the highest tomato yield at 96 360 kg ha^{-1} with the application of 864 mm irrigation water. In the present study, a very close yield (93 200 kg ha^{-1}) was obtained from I_{50}. Therefore, this study determined that the optimum planting interval for tomatoes grown in an open field should be 50 cm between rows and 33 cm inter-rows with a combination of 60 000 pph, since this causes the tomatoes to use water and radiation more efficiently as compared to the combination of 30 303 pph in the I_{100} treatment and 101 010 pph in the I_{30}.

There is no need to increase the planting density of 50x33 cm for more efficient utilization of nutrients and water in order to get a better marketable yield. The best combination for tomato yield in an open field was 60 000 pph, with an application of 128 kg NPK ha^{-1}. An increase in plant density reduces marketable fruit quality as competition between plants may be high for nutrients and water. On the other hand, a reduction in plant density lowered the yield significantly as plants were shading each other less, which decreased the water use efficiency of plants.

The planting density recommended here can be considered as an effective strategy for water management and achieving an economic yield.

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