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Influence of single and multiple water application timings on yield and water use efficiency in tomato (var. *First power*)

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ABSTRACT

A greenhouse experiment was conducted at Japan International Research Center for Agriculture Science (JIRCAS), Okinawa Subtropical Station, Ishigaki, Japan with three multiple water application and two single water applications to study the effects of them on tomato yield, soil water content and water use efficiency. Multiple water application is a technique use to add the required amount of water during irrigation in multiple equal parts a day instead of one complete set (single water application) during the irrigation event. The multiple water application treatments were the day time (DT), day–night time (DNT) and night time (NT) while the single water application treatments were morning time (MT) and evening time (ET). In multiple water irrigation treatments the water was added to the soil into three equal parts. The supplied irrigation water was the same for all treatments and gradually increased with plant age to cover the crop water requirement during the growing season.

The results revealed that multiple water application increased tomato yield by 5% over the highest yield of single water application. The DT treatment increased tomato yield by 5% and 15% compared to ET and MT treatments, respectively. For multiple water application, the DT was the best irrigation timing because it increases the tomato yield by 8% and 12% compared to DNT and NT, respectively. ET irrigation was better than MT irrigation for single water application. Multiple water application led to an increased in soil water content compared to single water application. By applying the same amount of water for all treatments, the DT treatment increased water use efficiency by 5–15% compared to ET and MT treatments of single water application. In conclusion, multiple water application is better than single water application and by choosing the proper irrigation timing, higher tomato yield resulting from efficient water management can be obtained.

1. Introduction

Irrigation timing plays an important role for increasing crop productions per unit of water especially in areas with limited water resources. Proper irrigation timing increases the water use efficiency; consequently the production per unit of water will be increased. Improper irrigation timing can lead to the development of crop water deficit resulting in reduced yield due to water and nutrients deficiencies (Wright, 2002). Therefore, research needs to be carried out on the effect of

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single and multiple water application timing on yield and water use efficiency (WUE). Multiple water applications during the day resulted in higher growth and water use efficiency as compared to early morning applications (Warren and Bilderback, 2004; Davis et al., 1985; Phene et al., 1985). Hartz (1999) reported that multiple water applications in a day is not practiced widely except on sandy soil during periods of high-crop water use. However, in such situations multiple applications during the day may be required to prevent plant water deficit and significant leaching of water and nutrients. Daily cyclic irrigation applied in a series of cycles comprised of an irrigation and a resting interval improved water use efficiency by 25–38% (Karam, 1993; Fare et al., 1993; Tyler et al., 1996).

The proper irrigation time could be at the early morning hours before 10:00 h to reduce evaporation of irrigation water and to reduce potential of wind blowing the irrigation water from the target area especially under sprinkler irrigation (Yeag et al., 1997). Ismail et al. (2007) found that irrigation at early morning (8:00 h) every 3 days increased tomato yield by 11% over irrigation at night time (20:00 h) every day. Ozawa (1998) reported that foliar water spraying at dusk reduced the plant water stress rapidly and accelerated root growth resulting in an increase in soil mass in which plant root were present. This increased water absorption during night and in the morning as well.

The objective of this study was to compare between multiple and single water application timings by evaluate their effects on crop production, soil moisture distribution, soil temperature and water use efficiency in tomato under subtropical conditions.

2. Materials and methods

The experiment was conducted in a greenhouse at the JIRCAS Okinawa Subtropical Station, Ishigaki, Japan. The soil inside the greenhouse is classified as a sandy loam soil. The climatic conditions inside and outside the greenhouse are similar. When the temperature or relative humidity inside the greenhouse is increased; an automated ventilation system starts working to adjust the climatic conditions again.

An automated drip irrigation system was used in the greenhouse. The timers and electrical valves automatically controlled the time and amount of irrigation water. The discharge of the dripper was 3.9 l/h and was the same for all drippers. It is calibrated by collecting the water in a plastic cup from each dripper several time under constant head flow. The detailed layout of the used drip irrigation system is presented in Fig. 1.

Five irrigation timings were studied, including three multiple daily irrigations and two single daily irrigations (Table 1). In multiple daily irrigation treatments the water was added to the soil into three equal parts. The first treatment represents the day time, the second treatment represents from the midday to midnight and the third treatment represents the night time. In single daily irrigations the water was added into the soil in one complete part with two treatments, morning time (8:00 h) and evening time (20:00 h). Each treatment was replicated two times with 14 plants in each replication.

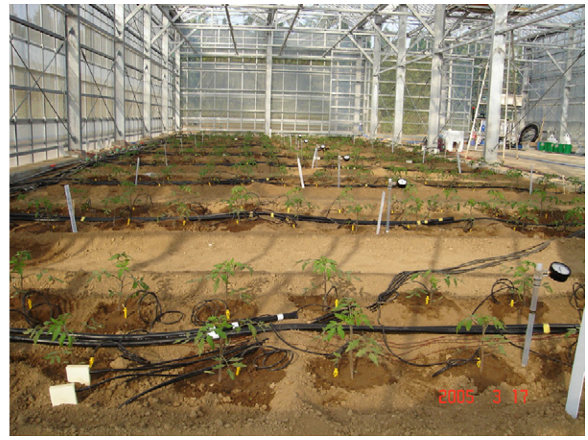

Fig. 1 – Layout of drip irrigation network.

Soil water content and soil temperature were measured at a distance of 15 cm from the dripper. Soil water content measured at 15, 50 and 85 cm soil depth by time domain reflection (TDR). CS616 water content reflectmeter sensors were installed vertically along each depth for all treatments. Soil temperature was also measured by installing thermocouples at 10, 20, 45 and 75 cm depth for each treatment. Soil water content and soil temperature data were recorded on a 30 min interval by CR23X data logger. The tomato (var. *First power*) seedlings were transplanted on 25 February 2005 (Julian Day 56) with two lines for each row. The row spacing was 1 m with plants spaced at 40 cm apart. The seedlings were manually irrigated by 250 cm^3 nutrient solutions during the first 3 weeks to support the development of root growth. After 3 weeks from transplanting, the irrigation treatment timings were followed. The supplied amount of water was the same for all irrigation timings, starting with 1.9 mm/day and gradually increased to 2.85 and 3.80 mm/day (average 2.85 mm/day) to cover the crop water requirements during each growing stage.

The plants were fertilized with a nutricoat fertilizer containing 14% N, 12% P_2O_5 and 14% of K_2O. A dosage of 10 g fertilizer was added twice, at 30 and 60 days of transplanting, at 10 cm below soil surface in the root area of each plant. At the starting of flowering stage, tomatotone hormone was sprayed equally for all plants once a week and up to the end of the growing season to enhance the fruit setting. The matured (red color) tomato appeared on 4 May 2005, since that, the harvesting season was started by collecting matured tomato twice a week. The fruit weight and numbers were recorded separately for each plant at every harvesting. The Rafrectometer was used to measure tomato fruits quality (mass sucrose % at 20 °C). Xylem water potential

Table 1 – Investigated treatments and their abbreviation

Treatments	Irrigation timings	Abbreviation
Morning	08:00 h	MT
Evening	20:00 h	ET
Day time	06:00 h, 12:00 h and 18:00 h	DT
Midday–midnight	12:00 h, 18:00 h and 00.00 h	DNT
Night time	19:00 h, 01.00 h and 07:00 h	NT

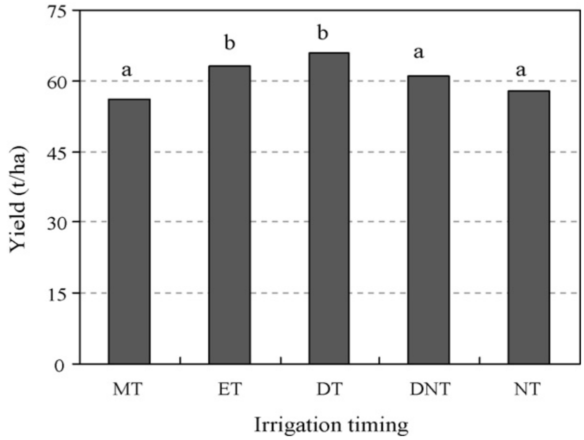

Fig. 2 – Tomato yield for all treatments (means with different superscripts differ significantly, $P < 0.05$).

was measured at 13:00 h for 7 consecutive days (Julian days 140–146) by measuring the leaf pressure. At the end of harvesting season (Julian days 167) three plants from each replication were cut to analyze the dry matter. The weight of stem, petiole and leaves were evaluated separately for each plant after dried at 70 °C. The statistical analysis has been done by statisica program (StatSoft Inc., 1995).

3. Results and discussions

3.1. *Crop yield*

Fig. 2 shows the tomato yields for all investigated treatments. Multiple water application during day time (DT) was the best with average tomato yield of 66 t/ha while the yield was 63, 61, 58 and 56 t/ha for ET, DNT, NT and MT irrigation timings, respectively, although, no significant differences were found between the yield of DT and ET treatments. The DT treatment increased the average tomato yield by 5% and 15% compared to single water application of ET and MT treatments, respectively. Moreover, DT treatment increased the average tomato yield by 8% and 12% compared to the multiple water application treatments of DNT and NT, respectively.

The increase in tomato yield in the treatments of DT and ET compare to the other treatments can be explained by the fruit weight and numbers. The high-tomato yield (66 t/ha) obtained from DT resulted from the significant increase in fruit number while the high-tomato yield (63 t/ha) for ET treatment resulted from the significant increase in fruit weights (Table 2). The most important factors, which have direct impact on fruit weight and number, were the soil water content and soil temperatures. Soil water content affected mainly the fruit weight while soil temperature affected mainly the fruit numbers; increasing soil temperature reduces fruit setting and consequently numbers (Ismail et al., 2007). The relationship between soil water content, irrigation timing and fruit weight revealed that higher soil water content increased the fruit weight and consequently the tomato yield. The higher yield of ET irrigation timing despite of its low-soil water content could be related to better root development, which may encourage the plants to explore a greater soil mass and thus increase the water absorption (Ismail et al., 2007).

3.2. *Fruit weight and numbers*

The fruit weight and numbers are presented in Table 2. Significant differences in average fruit weight and number were found between treatments. The average fruit weight for NT irrigation timing was the highest followed by MT, ET, DT and DNT in decreasing order. The highest fruit numbers were recorded in DT followed by DNT, ET, MT and NT timings, respectively.

As said previously, the mean reason for increasing the fruit weight is soil water content. The results of soil water content for NT treatments (Fig. 6) support that trend. It is known that 40% of plant water requirement is covered by the upper 25% of the plant roots however, under low-soil water content the lower roots are responsible for recovering the plant water requirements. It is expected that the MT and ET treatments developed lower roots and depleted more water, which resulted in higher fruit weight (Table 2) and lower soil water content (Fig. 6).

The increase in fruit number is due to the decrease in soil temperature; an increase in soil temperature decreased the number of fruit and tomato yield due to a decrease in fruit set. The results of average soil temperatures at 10 and 20 cm depth (Fig. 7) were in consistent with results of tomatoes yield (Fig. 2). The high-tomato yield was obtained from the treatments with low-average soil temperatures (Warren and Bilderback, 2004; Ismail et al., 2007).

3.3. *Shoot dry matter*

The shoot dry weight (stem, petiole and leaves) was presented in Table 2. The results indicated that, there were no significant

Table 2 – Results of fruits weight, numbers and shoot dry weight

Treatments	Average fruit weight (g)	Average fruit number (plant)	Average shoot dry weight (g/plant)			
			Stem	Petiole	Leaf	Total
MT	208	5.5	30.0	13.6	24.4	68.0
ET	203	5.9	28.9	13.6	26.2	68.7
DT	193	6.6	30.5	13.8	25.0	69.3
DNT	186	6.3	26.8	11.6	21.6	60.0
NT	221	5.0	28.6	12.2	23.8	64.6
$LSD_{0.05}$	5.52	0.417	3.08	2.44	3.99	4.44

differences in stem and petiole dry weights for all treatments except for DNT treatment. The stem and petiole dry weights of DNT treatment were significantly less than the others. Significant differences in leaf dry weight were found between treatments. The highest leaves dry weight resulted from the ET treatment followed by DT, MT, NT and DNT treatments, respectively. The difference in leaf dry weights of DT and ET treatments was not significant. The highest increase in total shoot dry weights obtained from DT treatment compared with the other treatments; however, the increase was not significant compared with ET treatment.

The total shoot dry weight indicated that DT irrigation timing produced the highest shoot dry weight. These results may be due to two reasons. The first one is the higher soil water content. The DT irrigation timing has higher soil water content compared to ET and MT irrigation timings (Fig. 6). Higher soil moisture content increase shoot dry weight while low-soil moisture content resulted in reduced shoot and leaves dry weights. The reduction in shoot or leaves dry weight under soil moisture deficit may be due to lateral root elongation resulting in a decrease in shoot to root ratio (Singandhupe et al., 2003).

The second reason could be root development and nutrients availability; the soil water content of DT irrigation timing was lower than that in DNT and NT irrigation timings although its shoot dry weight was higher than both of them. Low-soil water content conditions encourage plant root development which can explore greater soil mass and increase the water and nutrients absorption resulting in higher shoot dry weight. The maintenance of a proper balance between root and shoot development is important, if either of the two is too limited or too great in extent, the other will not thrive (Leskovar and Boales, 1995; Ismail et al., 2007).

3.4. *Xylem water potential*

Xylem water potential depends on the water uptake rate of plants; however the water extraction rate from soil profile is governed by the availability of moisture in soil profile. Under inadequate water supply, the xylem water potential decreases and it increases under adequate water supply. Fig. 3 shows the xylem water potential measured at 13:00 h for 7 consecutive days. The xylem water potential was the highest in DNT and the least in DT irrigation timings, respectively. No clear differences were found in the other treatments (MT, ET and NT).

The highest xylem water potential was measured in DNT irrigation timing. That treatment received one part of multiple water application at 12:00 h resulting in rapid increase in xylem water potential which measured after 1 h of the irrigation event (13:00 h). A similar part of irrigation water was also supplied to the DT irrigation timing at the same time (12:00 h) but the xylem water potential was the lowest indicating that the xylem water potential was affected by the tomato yield beside irrigation timings (Figs. 2 and 3). High-fruit density may have exerted an additional pressure on the roots to extract more water from soil to divert to the fruit instead of leaves resulting in low-xylem water potential.

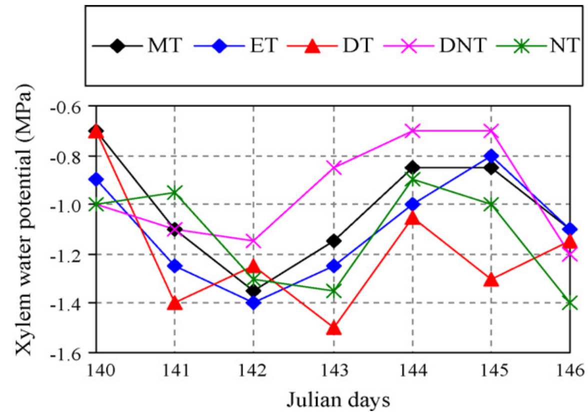

Fig. 3 – Xylem water potential of 7 consecutive days for all treatments.

3.5. *Yield quality*

One of the aims of this study was to maximize the production per unit of water use regardless of the quality; however, the fruit quality was investigated to know the relationship between it and the available soil moisture. Fig. 4 shows the relationship between total soluble solids content (Brix) and yield. The results indicated that there was an opposite relationship between tomato quality and quantity. Increasing tomato yield decreases Brix content. The highest Brix content resulted from the treatment of MT irrigation, which produced the least tomato yield (56 t/ha) followed by NT treatment. Small differences in Brix content were found between DT, DNT and ET irrigation timings.

The reduction in Brix content resulted from the increase in available soil moisture. Under high-available soil moisture the root may absorb more water. Absorbing more water resulted in and increase in fruit weight and a reduction in the total soluble solid due to the dilution by water. Fig. 5 confirmed this relationship, that increasing soil water content led to a decrease in Brix content. To increase the quality of tomato yield the soluble solid contents should be increased by decreasing the amount of water supply at the beginning of the maturation stage (Marouelli et al., 2004).

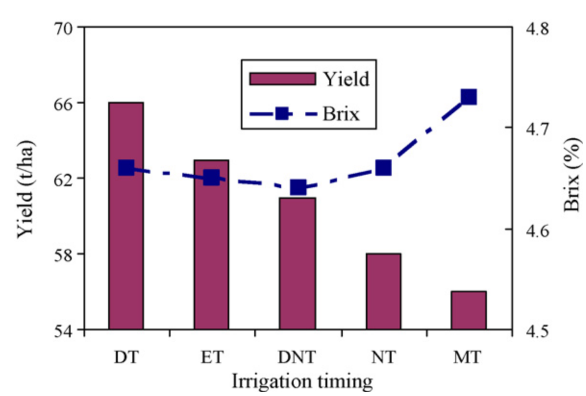

Fig. 4 – Brix content in relation to yield.

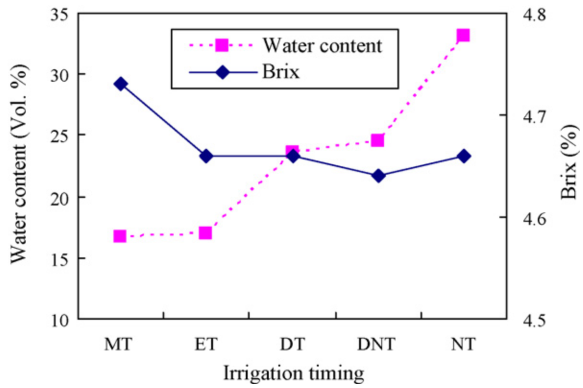

Fig. 5 – Effect of soil water content on Brix content in tomato.

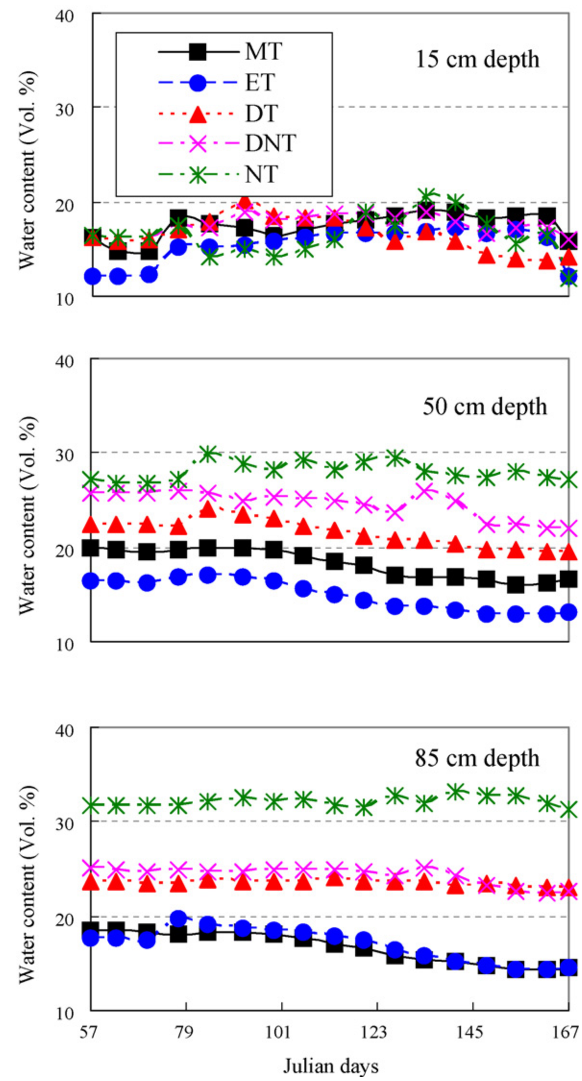

Fig. 6 – Average soil water content distributions at different soil depths during the growing season.

3.6. *Soil water content distribution*

The distributions of soil water content at three different depths (15, 50 and 85 cm) were presented in Fig. 6. The results revealed that the soil water content at 15 cm was less than that at 50 and 85 cm depth in all treatments. There was no clear trend or large differences between treatments at that surface layer (15 cm depth).

At 50 cm depth the distribution of soil water content was very clear. The highest soil water content measured for NT irrigation timing followed by DNT, DT and MT irrigation timings, respectively. The lowest soil water content was recorded for ET irrigation timing. Similar distribution was found at 85 cm depth showing that there were large differences in soil water content distribution between treatments. The highest soil water content was recorded for NT irrigation timing revealing large differences compared to the other irrigation timings. The soil water content for DT and DNT were almost the same but lower than that in NT irrigation timing. The lowest soil water content was measured for ET and MT irrigation timing but both of them were similar especially during the last month of the growing season when the soil water content decreased sharply compared to other treatments.

The low-soil water content at 15 cm depth for all irrigation timings may be due to increased evaporation from soil surface along with transpiration. About 70% of the plant roots were present at the upper soil layer (15 cm). These roots supplied the majority of the plant water requirement by depleting more water from 15 cm than from 50 and 85 cm soil layer. The low-soil water content at 15 cm depth at the first 3 weeks of the growing season resulted from a little amount of water supply (250 cm^3). The applied amount moist only a thin layer of soil surface, which was easy to evaporate and resulted in a sharp decrease in soil water content.

The variations in soil water content between treatments at 50 and 85 cm depth are due to three reasons. The first reason is the method of water supply; the supplied water in multiple water application added to the soil into three equal parts. Dividing the irrigation water to three equal parts during the day reduced the evaporation especially during the day time resulting in high-soil water content of multiple water application than single water application. The NT treatment resulted in the highest soil water content because during night time the evaporation is minimal, the infiltration is high resulted in the highest soil water content. The second reason is root development. It is known that the root developed where soil water content is presented. The frequent light irrigations result in shallow root systems, led to a variation between the treatments. The variation was in consistent with the time of application; the highest soil water content found in NT, DNT, DT, MT and ET, respectively. The third reason is tomato yield; an increase in the number of fruits in plants exerted an additional pressure on roots to extract more water from soil in order to meet the crop water requirement, resulted in low-soil water content especially ET and MT treatments (Fig. 6) and high yield (Fig. 2).

3.7. *Soil temperature*

The results in Fig. 7 show the variations in average daily soil temperature measured for 3 consecutive days (123–125 Julian

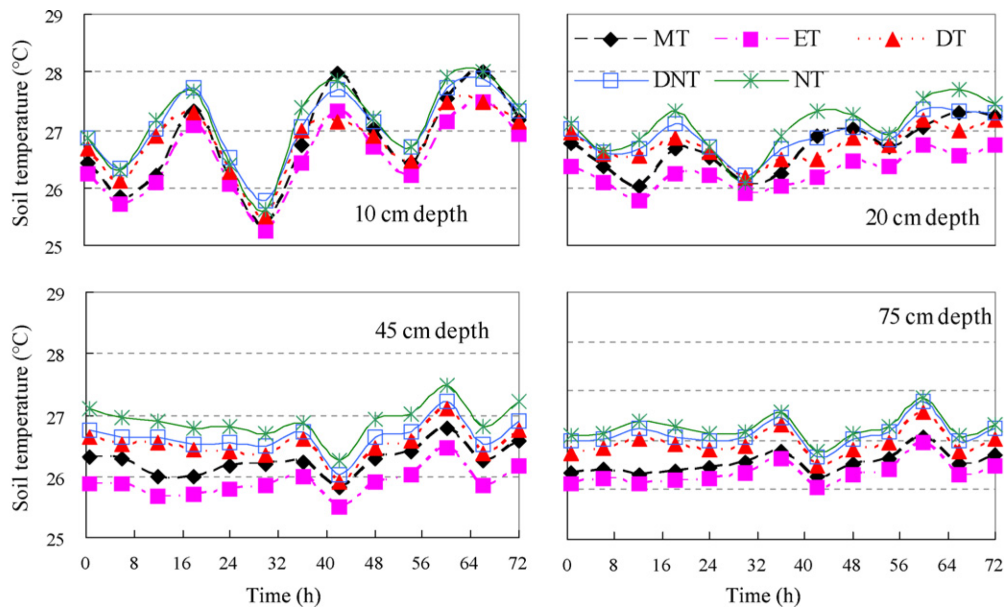

Fig. 7 – Average daily soil temperatures for 3 consecutive days (123–125 Julian days) at various soil depths.

days). The differences in average soil temperature at 10 and 20 cm depth were small (less than 1 °C). The lowest soil temperature was obtained from ET irrigation timing followed by DT and MT irrigation timings, respectively, while the latter treatments showed no differences. The highest average soil temperature recorded for DNT and NT irrigation timings. At 45 and 75 cm depth the variations in average soil temperature in the treatments were clear. The highest average soil temperature measured for NT irrigation timing followed by DNT, DT, MT and ET irrigation timings, respectively.

The results of soil temperatures revealed that the multiple water application treatments (DT, DNT and NT) increased average soil temperature compared to single water application treatments (MT and ET). Higher soil water content in multiple water application treatments may be the reason for higher soil temperature. A comparison of soil temperature distribution along the soil depth (Fig. 7) and soil moisture distribution

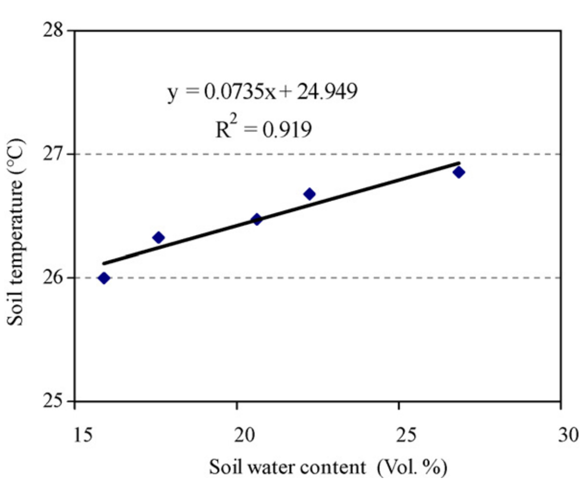

Fig. 8 – The relationship of soil temperature and soil water content under the condition of this experiment.

(Fig. 6) revealed that the large increase in soil water content caused a small increase is soil temperature (Fig. 8). As shown in Fig. 8 increasing soil water content from 16% to 27% increased the soil temperature by less than 1 °C. The increase in soil temperature due to the increase in soil water content could be related to the thermal diffusivity of sand content which constitute 69.4% of this soil. The thermal diffusivity of wet sand is higher than that of dry sand. Another specific reason for this soil is that, the thermal conductivity of wet soil is higher than that of dry soil.

3.8. *Water use efficiency*

Table 3 shows the water use efficiency (WUE), which represented by the production of yield in kg/(mm ha). The WUE was obtained from dividing the total yield in kg/ha by the total water supply in mm/ha (313.5 mm/ha). The higher the production, the higher the water use efficiency since total water supply is the same for all treatments. The results revealed that, there is a significant difference between treatments. The DT irrigation timing gave the highest water use efficiency followed by ET, DNT, NT and MT irrigation timings, respectively.

Table 3 – Water use efficiency for the investigated treatments

Treatments	Average production (kg/(mm ha))	Increase in yield or WUE relative to morning irrigation timing (%)
MT	180	–
ET	200	10
DT	211	15
DN	197	9
NT	185	3
$LSD_{0.05}$	12.96	

The highest water use efficiency obtained from DT irrigation timing was because of the highest yield in this treatment (211 kg/(mm ha)). This suggested that, giving the same amount of water for all treatments, the DT irrigation timing of multiple water application increased water use efficiency by 15% compared to MT irrigation of single water application.

4. Conclusions

Multiple water application increased tomato yield compared to single water application. The DT irrigation of multiple water application increased the tomato yield or water use efficiency by 5–15% compared to ET and MT treatments. ET irrigation was better than MT irrigation for single water application because it increased the yield by 11%. Increasing tomato yield decreased total soluble solids content (Brix). Multiple water application increased soil water content and soil temperature compared to single water application. In conclusion, multiple water application is better than single water application and by choosing the proper irrigation timing efficient water use or higher tomato yield can be obtained.

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