EFFECT OF IRRIGATION FREQUENCY AND TIMING ON TOMATO YIELD, SOIL WATER DYNAMICS AND WATER USE EFFICIENCY UNDER DRIP IRRIGATION

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ABSTRACT

Two experiments were carried-out to study the effect of irrigation frequency and timing on root developments, tomato yield (*var. First power*) and soil water content at JIRCAS Okinawa Subtropical Station, Ishigaki, Japan. The first experiment was conducted in root containers (31 x 15 x 60 cm) with one transparent side for visual viewing of the root development. Sandy clay loam soil mixed with $CaCO_3$ and P_2O_5 fertilizers was packed in the containers to 50 cm height with bulk density of 1.5 g/cm^3. Three irrigation frequencies, 1, 3 and 5 days were investigated. The soil water content in the containers was kept at field capacity by compensating the loss in weight by adding water. The second experiment was conducted in a greenhouse with two irrigation frequencies, 1 and 3 days and three irrigation timings, early morning (8:00h), afternoon (14:00h) and night (20:00h). Soil water content at 0-60 cm and soil temperature at 15 cm depth were measured at 15 cm distance far from dripper by installing TDR sensors and thermocouples, respectively. The supplied amount of water was the same for all irrigation frequencies and gradually increased to cover the crop water requirements during each growing stage.

The root containers results indicated that increasing water supply increased the root development and root biomass. The 1-day irrigation frequency produced the highest root biomass while the least root biomass was obtained from the 5-days irrigation frequency, indicating that water stress promoted the development of root system in the deeper layer where available soil moisture content was higher than the top layers. The 5-days irrigation frequency saved 18% and 12 % of water at early growth stage compared to 1 and 3 days frequencies.

The results of greenhouse experiment showed that the best irrigation frequency was 3-days. The average yield in 3-days frequency was 70 ton/ha while 63 ton/ha in 1-day frequency. The effect of irrigation timing varied with irrigation frequency. For 3-days frequency, irrigation at early morning was better than afternoon and night irrigations. The average yield for irrigation at early morning was increased by 15% and 14% than irrigation at afternoon and night, respectively. For 1-day frequency irrigation at night increased the yield by 11% and 3% than irrigation at early morning and afternoon correspondingly. The lowest soil water content and soil temperature were displayed by the treatment, which produced the highest yield. With the same amount of water, the early morning irrigation after every 3-days increased tomato yield by 11- 20 % compared to night and early morning irrigation of 1-day frequency. A similar increase in water use efficiency in the early morning irrigation every 3-days was also recorded. Therefore, a selection of the proper irrigation frequency and timing led to a higher yield and high water use efficiency.

Keywords: Irrigation timing, frequency, root development, tomatoes

INTRODUCTION

Poor irrigation timing can lead to the development of crop water deficit and result in reduced yield due to water and nutrients deficiency. Moreover, proper time of irrigation is essential to the production quality of the most vegetables. If water shortages occur early in the crop development, maturity may be delayed which may reduce yields. The moisture shortage later in the growing season adversely affects the quality of produce even though total yields may not be affected.

The soil in the germination and early growth root zone should be moist at the time of planting. If necessary, irrigation should take place to wet this zone. As the plant grows, moist soil is necessary for proper root development, as roots will not grow through a dry layer of soil. A dry layer will result in a shallower rooting depth than is desirable [19]. Soil profile should be filled with water at each irrigation. Frequent light irrigations result in shallow root systems. Shallow root systems result in plants being stressed even in short periods of water deficit [14]. Early in the season when plants are small, it is beneficial to encourage roots to explore as much of the soil profile as possible. This maximizes nutrient uptake and maximize stress tolerance later in the season. The best approach to early season irrigation is to begin with a full soil profile and encourage deep rooting by not watering routinely, but rather waiting until the 20 % depletion of available water is reached at the appropriate monitoring depth. This may mean going from 5-7 days or longer between irrigation depending on the weather, the interval would be less in hot weather [3]. Water stressed conditions encourage tomato to develop its root system at deeper soil layers which retained more water [11].

The proper irrigation time could be at the early morning hours before 10:00h to reduce evaporation of irrigation water and to reduce potential of wind blowing the irrigation water from the target area especially under sprinkler irrigation [17, 20]. On the other hand, irrigation during the night time may be also better for crop because it is reduce evaporation of irrigation water, give the chance for moving the irrigation water to deep layer that can be extracted by deep roots, consequently increase water use efficiency. Foliar water spraying at dusk reduced the plant water stress rapidly and accelerated root growth. Then it increased the soil mass that plants are present in, the soil mass that was spread increase water absorption in the morning as well [11]. The challenge of water management at the crop level is to mach the time course of irrigation resources by increasing the resources, moderating plant requirements and or increase soil water extraction [2].

The objectives of this study was to study the relationship between irrigation frequency and root development and to find the appropriate irrigation frequency and timing which can maximize crop production and water use efficiency in tomato.

MATERIALS AND METHODS

The experiments were carried out in a greenhouse situated at JIRCAS Okinawa Subtropical Station, Ishigaki, Japan.

1) Effect of irrigation intervals on tomato root growth in root containers

Root containers experiment was conducted to study the relationship between irrigation frequency and root development. The container size was 31 x 15 x 60 cm with one transparent side for visual viewing of the root development. Sandy clay loam soil with bulk density of 1.5 gr/cm^3 mixed with $CaCO_3$ and P_2O_5 fertilizers was packed in the containers to 50 cm height. One tomato (*var. first power*) seedling was transplanted in the middle of each container at the 7 of February 2005. Three irrigation frequencies, 1, 3 and 5 days with four replicates were followed. Before the start of the treatments the containers were saturated with water while they were kept at the field capacity during the growth period. The development of roots was observed from the transparent side of the containers. The plants were harvested after three weeks. The weight of the aboveground biomass was recorded after dried at 70 ºC. The roots for each 10 cm depth were collected separately and washed and weighted after dried at 70 ºC to study the roots mass over depth for each irrigation frequency.

2) Effect of irrigation interval and timing on growth characteristics and yield

The detailed descriptions of soil physical properties in the greenhouse used for the experiment were presented in Table 1. An automated drip irrigation system was followed in the greenhouse.

The timers and electrical valves automatically controlled the time and amount of irrigation water. The row spacing inside the greenhouse was 1 m with two lines of plants spaced 40 cm apart. The discharge of the dripper was 3.9 L/h. Two irrigation frequency 1 and 3 days were investigated. Under each irrigation frequency, three irrigation timings were followed: early morning (8:00h), afternoon (14:00h) and night (20:00h). Each irrigation time was replicated 3 times with 10 plants in each replication. The tomato seedlings were transplanted in 25 February 2005. The seedlings were manually irrigated by 250 ml nutrient solution for three weeks to support the development of root growth. After 3 weeks from transplanting, the irrigation frequency and timings were followed.

Table 1 Soil physical characteristics inside the greenhouse

Characteristics		Surface (0-25 cm)	Sub-surface (25-50 cm)
Particle size analysis	Clay %	9.5	10.8
	Silt %	24.5	20.0
	Sand%	66.1	69.2
TEXTURE GRADE		Sandy loam	Sandy loam
Organic matter %		2.8	2.3
Welting point cm^3/cm^3		0.09	0.09
Field capacity cm^3/cm^3		0.19	0.19
Saturation cm^3/cm^3		0.41	0.41
Sat. hydraulic conductivity cm/hr		2.68	2.34
Available water cm^3/cm^3		0.11	0.11
Bulk density g/cm^3		1.56	1.55

The supplied amount of water was the same for all irrigation frequencies started with 1.9 mm/day and gradually increased to 2.85 and 3.8 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% 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.

Soil water content and soil temperature were measured at a distance of 15 cm from the dripper. Soil water content was measured at the upper 60 cm soil depth by Time Domain Reflection (TDR) method. CS616 water content reflectmeter sensors were installed vertically in the upper 60 cm depth in each treatment. Soil temperature was also measured by installing thermocouple at 15 cm depth. Soil water content and soil temperature data were recorded every 30 minutes interval by CR23X data logger. At the end of harvesting season three plants from each replicate were harvested to analyze the dry matter. The weigh of shoot and leaves were evaluated separately for each plant after dried at 70 ºC. Xylem water potential was measured at 13:00h for 7 consecutive days (20-26 May) by measuring the leaf pressure.

RESULTS

1) Results of root containers experiment

The results of the average shoot and root dry weights, total water supply and root-shoot ratio are presented in Table 2. The results indicate that the shoot and root dry weights was decreased by an increase in irrigation interval. The shoots and roots dry weight for 1-day irrigation frequency was higher than 3 and 5 days frequencies. The root-shoot ratio for 1 and 5 days irrigation frequencies were similar but were look lower than that of 3-days frequency. Increasing irrigation intervals reduced the amount of water supply. The amount of water supply for 1-day irrigation frequency was the highest. Increasing the irrigation interval led to an increase in water use efficiency (amount of water used to produce 1 g of dry weight). The 5 and 3 days irrigation frequencies saved 18% and 7% of irrigation water compared to 1-day irrigation frequency, respectively however, using 5-days frequency is not recommended under hot weather conditions like that prevailed in Ishigaki.

Table 2 Effect of irrigation interval on plant growth characteristics

Irrigation interval (day)	Total water supply L/plant	Root dry weight (g)	Shoot dry weight (g)	Root-shoot ratio	Consumed water L/g
1	1.468 ± 0.12	0.281 ± 0.09	3.06 ± 1.10	0.09 ± 0.02	0.44 ± 0.11
3	1.278 ± 0.07	0.271 ± 0.09	2.82 ± 0.61	0.10 ± 0.04	0.41 ± 0.08
5	1.066 ± 0.07	0.241 ± 0.09	2.76 ± 0.52	0.09 ± 0.03	0.36 ± 0.05

Average ± SD

Figure 1 shows the dry weight distribution of roots over 0-50 cm soil depth. The results indicate that 60 to 75% of the roots dry weight was present in the 0-10 cm layer for all irrigation frequencies. The roots dry weight was higher in 1-day than the remain irrigation frequencies up to 40 cm depth. On the contrary the roots dry weight from 40-50 cm depth was increased by increased irrigation intervals. The roots dry weight in 5-days irrigation frequency was higher than in 1 and 3 days frequencies. The roots reached the bottom of the containers, lay down and then started branching and developed the lateral roots.

2) Results of growth characteristics and tomato yield

2.1) Crop yield

Figure 2 shows the yield for 1 and 3 days irrigation frequencies and for the three irrigation timings (early morning, afternoon and night).

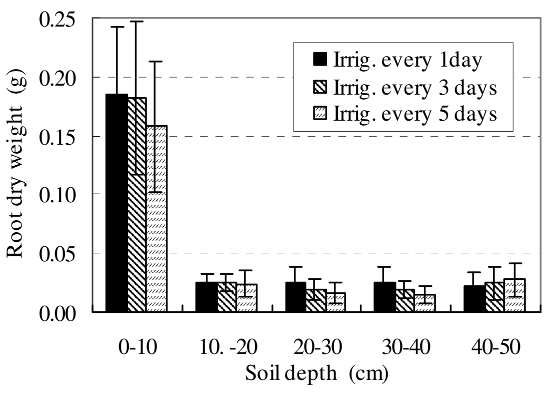

Figure 1 Roots dry weight distribution in the upper 50 cm soil depth

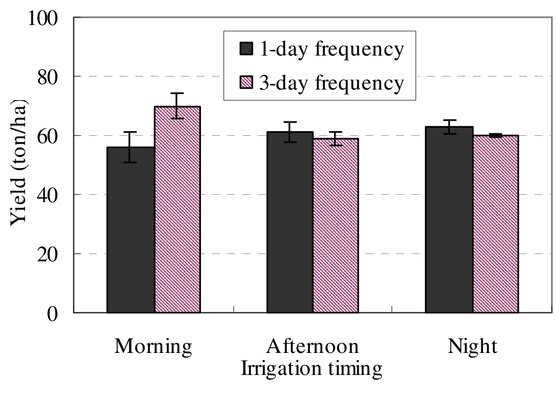

Figure 2 Tomato yield for both irrigation frequencies and timings

The results indicated that the 3-days irrigation frequency increased the average yield by 10% over the highest yield of 1-day irrigation frequency. The average yield for 3-days irrigation frequency was 70 ton/ha while 63 ton/ha for 1-day frequency. The results of 1-day irrigation frequency indicated that irrigation at night was better than early morning and afternoon, respectively. The average yield was 56, 61 and 63 ton/ha for early morning, afternoon and night irrigation, respectively. However, for 3-days frequency, irrigation at early morning was the best. Irrigation at early morning produced 70 ton/ha yield while irrigation at afternoon and night produced 59 and 60 ton/ha, respectively.

2.2) Fruit weight and numbers

The fruit weight and numbers per plant are presented in Figure 3. The results revealed that the average fruit weight for 1-day irrigation frequency was higher than that of 3-days frequency. The average fruit weight for early morning and night irrigations was higher than that in afternoon irrigation for both 1 and 3 days frequencies. The variation in fruit number due to irrigation frequency was very small while the variations due to irrigation timing were high. For 1-day irrigation interval, the fruit number for night irrigation was higher than early morning irrigation. For 3-days irrigation frequency, early morning and night irrigation timings produced the same fruit numbers but higher than in afternoon irrigation. The result of fruit numbers and fruit weight were in line with the total crop yield results (Fig. 2) indicating that the high crop yield (63 ton /ha) obtained from night irrigation for 1-day irrigation frequency resulted from the increase in fruit number. However, the high crop yield (70 ton/ha) for 3-days irrigation interval resulted from a combination of the increase in fruit numbers and weights.

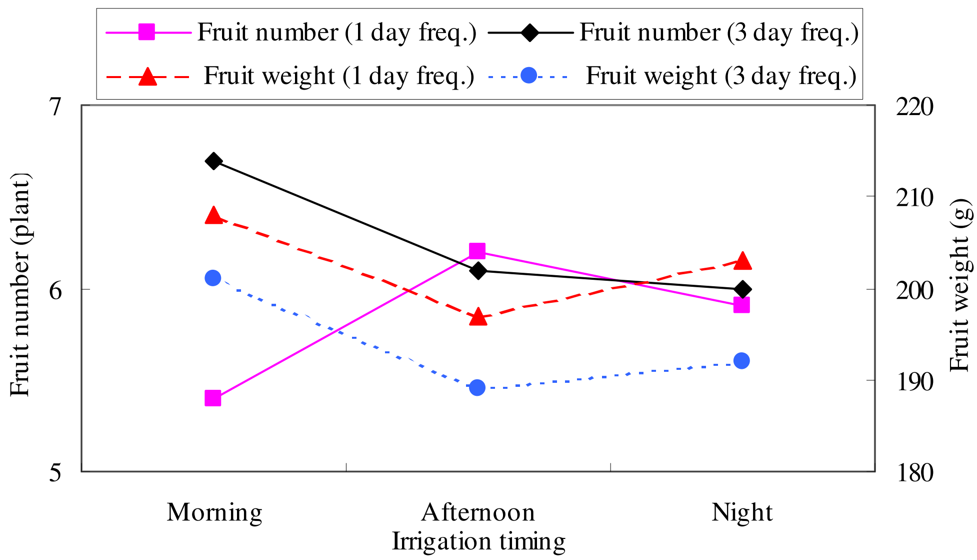

Figure 3 Weight and number of fruits for both irrigation frequencies and timings

2.3) Shoots and leaves dry weights

Figures 4 and 5 show the shoot (stem, petiole and leaves) and leaf dry weights for both irrigation frequencies and all irrigation timings. The results indicate that there were small differences in shoot and leaf dry weights between the two irrigation frequencies and three irrigation timings.

2.4) Xylem water potential

Figure 6 shows the xylem water potential measured at 13:00 h for 7 consecutive days (20 to 26 May, 2005). The results of 3-days frequency revealed that the xylem water potential of the early morning irrigation was the lowest followed by night irrigation and afternoons timing in an ascending order. The behavior of xylem water potential of the afternoon and night irrigation timings for 1-day frequency was not clear, however, the xylem water potential for afternoon irrigation was lower than that for the night irrigation. The highest xylem water potential obtained from the early morning irrigation timing compared to the other irrigation timings for 1-day frequency.

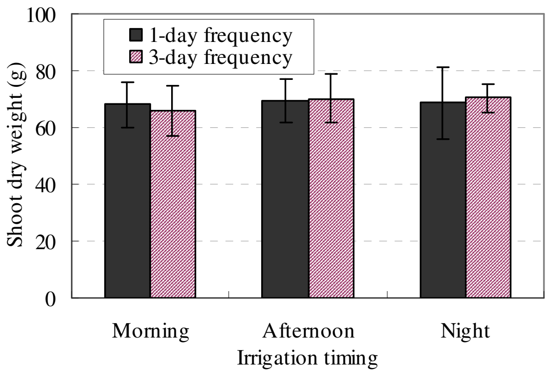

Figure 4 Shoot (Leaf, Petiole and stem) dry weights for both irrigation frequencies and timings.

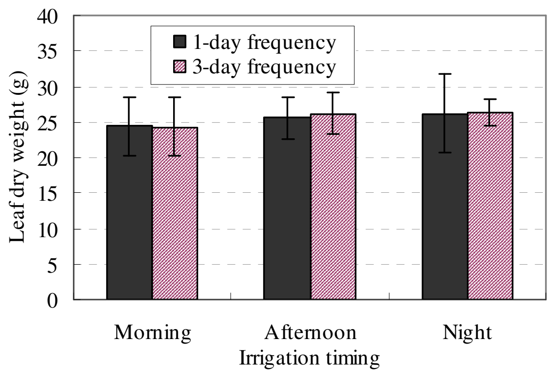

Figure 5 Leaf dry weights for both irrigation frequencies and timings.

3) Soil water content distribution

Figure 7 shows the average water content distribution at the upper 60 cm soil depth for all irrigation timings of 1 and 3 days frequencies during the growing season (110 days). The distribution of soil water content can be divided into three stages. The first stage was during the first three weeks after transplanting in which low soil water content was recorded for all irrigation timings. During that stage 250 cm^3 of water was added manually and equally in all treatments to support faster root development. The second stage showed gradual increase in soil water content for all treatments and continued for two months. Through out this stage, the water was applied by automated drip irrigation network. The amount of applied water was gradually increased depending on the growth stages of the plants. The amount of applied water was equal for all plants but application time was different according to the irrigation timings and frequencies. The third stage showed reduction in soil water content compared to the second stage. In this stage the soil water content was less than in the second stage and higher than soil water content of the first stage. The soil water content of the third stage was characterized by constant distribution rate until the end of the growing season. The results revealed that the soil water content of 3-days frequency was higher than soil water content of 1-day irrigation frequency. In 1-day irrigation frequency, irrigation at afternoon resulted in lower soil water content compared to soil water content of early morning and night irrigation timings. The soil water content for early morning and night irrigations were almost the same during the whole growing season except during the last three weeks when the soil water content for early morning was higher than the night irrigation. The results of soil water content of 3-days frequency were different than that in 1-day frequency. The soil water content of early morning irrigation was lower than the soil water content of afternoon and night irrigations. Moreover, the variation in soil water content of early morning irrigation was same during the whole growing season except before the start of the treatments. The differences in soil water content between second and third stage for early morning irrigation were not clear. The soil water content of the afternoon and night irrigation timings was similar during the whole growing season except during the first week after applying irrigation treatments when the water content for afternoon irrigation was high compared to the other timings.

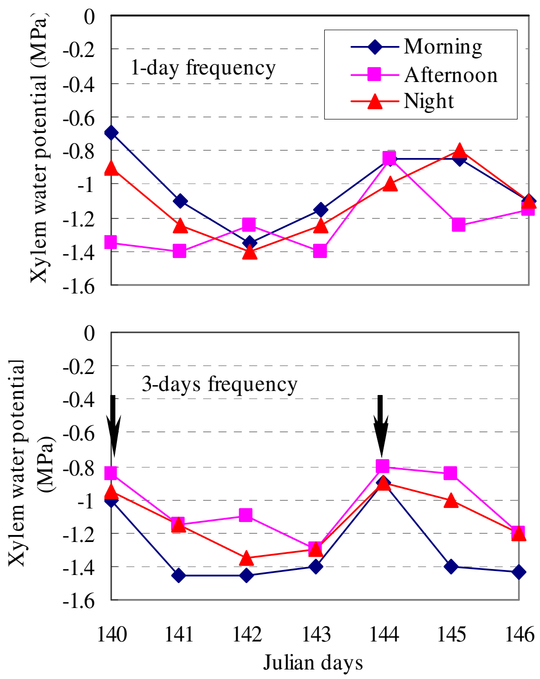

Figure 6 Xylem water potential of 7 consecutive days for both irrigation frequencies and timings.

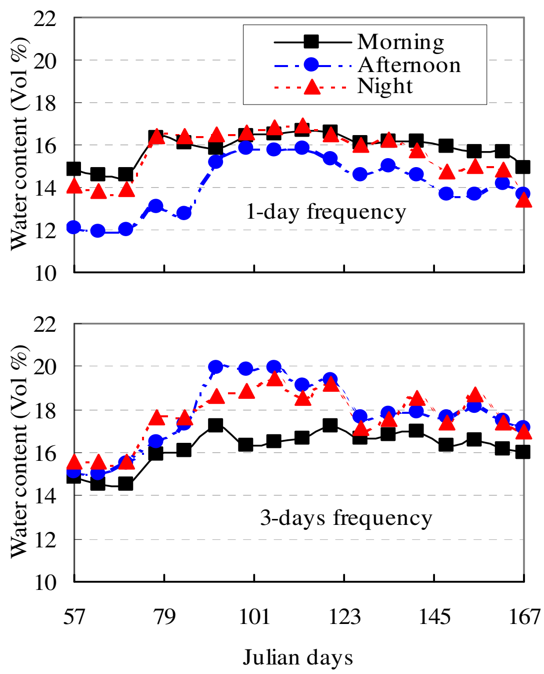

Figure 7 Water content distribution at the upper 60 cm of soil surface during the growing season of tomato.

4) Soil temperatures

The result in Figure 8 shows that the variation in average daily temperatures was affected by irrigation timings rather than irrigation frequencies. In 1-day irrigation frequency, irrigation at early morning increased the average soil temperature especially around 16:00h compared to irrigation at afternoon and night timings. The average soil temperatures for the irrigation timings of afternoon and night were similar. For 3-days irrigation frequency, the highest average soil temperature was measured in the afternoon irrigation while the lowest measured in early morning. The 1-day irrigation frequency led to an increase in soil temperature of early morning irrigation while 3-days frequency increased the soil temperatures of afternoon irrigation.

5) Water use efficiency

Figure 9 shows the amount of water used to produce 1 kg of tomato yield under the condition of this experiment for both irrigation frequencies and timings. The lower the amount of water used to produce 1 kg tomato, the higher the water use efficiency. The results revealed that early morning irrigation for 3-days frequency gave the highest water use efficiency while early morning irrigation for 1-day frequency gave the smallest. Applying water early morning after 3 days interval can save 11% - 20% of the irrigation water relative to 1-day frequency without affecting the crop yield.

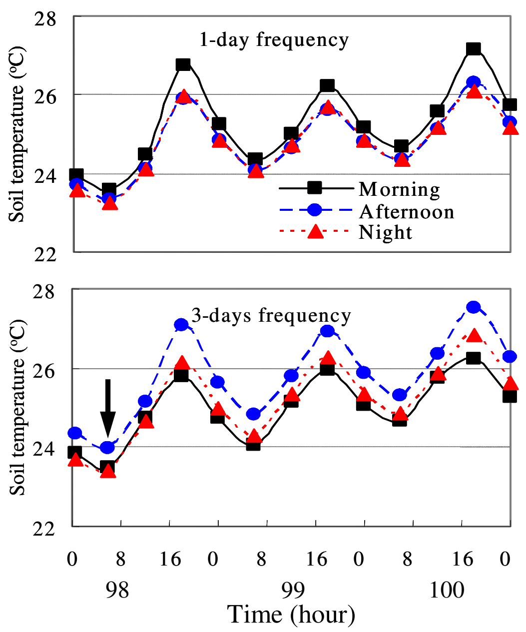

Figure 8 Average daily soil temperatures for 3 Julian days (98, 99 and 100) at 15 cm below soil surface for both irrigation frequencies and timings (day 98 was the irrigation day).

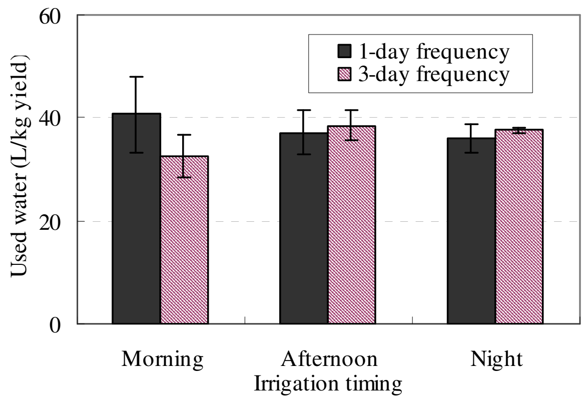

Figure 9 Amount of water produced 1 kg of tomato yield for both irrigation frequencies and timings.

DISCUSSION

1) Root growth

The condition of limited water supply in the soil to support plant growth is the most common form of stress that plants face. Water stressed plants generally exhibit a small root system configuration and the reduction in root system size is directly proportional to the magnitude of water shortage as indicated by the result presented in table 2, in which decreasing water supply reduced root dry weight because the pattern of root distribution was similar to the moisture distribution [9]. Decreasing root system due to water stress leads to a decrease in shoot dry weight because there is a close correlation between roots and shoot development. The maintenance of a proper balance between them is great importance. If either is too limited or too great in extent, the other will not thrive. Table 2 shows that the root-shoot ratios for 1and 5 days frequencies were the same, (0.09). Sometimes soil water deficits reduce shoot growth before root growth was reduced, resulting in increase in root-shoot ratio (3 days frequency Table 2) because roots grew more than leaves during a period of water stress. Much carbohydrate accumulates into roots, because deceleration of upper plant growth by water stress decreases the carbohydrate translocation to upper plant parts. Much carbohydrate accumulation into roots decreases the root osmotic potential and increases root turgor potential, which lead to enhanced root growth [12]. Irrigation method and timing are often used to reduce shoot to root ratio [6,8,18].
Root growth extends in all directions and if it encounters an area high in moisture or minerals it grows and branches profusely because of the less resistance in the wet soil [6]. This was displayed in 3 and 5 days irrigation frequencies, in which the roots grew rapidly downward (40-50 cm depth) to high soil moisture content resulting in higher root dry weight than in 1-day frequency (Figs 1). Under water stressed conditions tomato plants developed the roots in the deeper soil where high soil moisture content was available [11]. Sometimes water stress alters the root system structure by promoting the production of long lateral roots that emerged from the basal portion of the taproot thus making the direction elongation of these lateral roots more downward [6,19]. Irrigation method, rates, timing and frequency affect temporal and spatial nutrient concentration, pH, root medium electrical conductivity, physical and chemical properties of the growing media thereby affecting root initiation, elongation, branching, development and dry matter portioning between root and shoots. That mean soil water stress does not exist in isolation but it is mutually interactive with soil air and strength, all of which compounded together to affect the root growth [7,16].

2) Yield and soil temperature

The results of yield (Fig. 2) indicate that irrigation at early morning every three days was the best compared to all irrigation treatments (frequencies and timing). The differences in yield can be explained by the fruit weight and number. The high yield of early morning irrigation of 3-days frequency resulted from a combination of higher fruit weight and numbers while the increase in yield of the night time irrigation for 1-

day frequency resulted from fruit numbers only (Fig. 3). The most important factors, which have direct impact on fruit weight and number, were the soil water content and soil temperatures. However, soil water content affected mainly the fruit weight. The relationship between soil water content, irrigation timing and fruit weight (Fig. 11) revealed that higher soil water content increased the fruit weight for 1-day frequency, however the relationship is not clear for 3-days frequency.

In many studies the increase in tomato yield for the soil with high organic matter content correlated to the higher available water content due to the enhancement of water infiltration and water holding capacity result from the high organic matter in the soil [1]. The early morning irrigation timing for the 3-days frequency gave the highest yield (Fig. 2) while its soil water content was the least. This could be due to good root system developments below 60 cm soil depth, which encourage the plants to explore greater soil mass and increase the water absorption and consequently higher yield. Figure 1 proved that the roots development for 3-days irrigation frequency at the deeper soil was higher than that for 1-days frequency.

The soil temperature plays a major role in fruit numbers. An increase in soil temperature decreases fruit setting dramatically (Fig. 10), which resulted in a decrease in fruit numbers, consequently a large decrease in yield. The results of average soil temperatures (Fig. 8) for both irrigation frequencies were in consistent with results of yield (Fig. 2). The high yield obtained from the treatments, which have low average soil temperatures in both irrigation frequencies. The results of soil temperature also revealed that soil thermal conductivity under wet condition was higher than that under dry condition because the highest soil temperature obtained from the day of irrigation as indicated by the arrow in figure 8 for 3-day frequency. The differences in soil temperature in combination with available soil water content could have a significant impact on crop yields [10,13,17].

3) Shoot and leaf dry weights

The results showed an opposite trend between dry weights and yield for 3-days frequency. Increasing dry weights led to a decrease in yield (Fig. 2). The low soil moisture content resulted in reduced shoot and leaf dry weights [15]. An inadequate amount of available water in soil hampers various physiological processes in plant and finally the crop yield. The reduction in shoot or leaf dry weights under high moisture deficit may be due to lateral root elongation resulting in a decrease in shoot to root ratio [5,7,15].

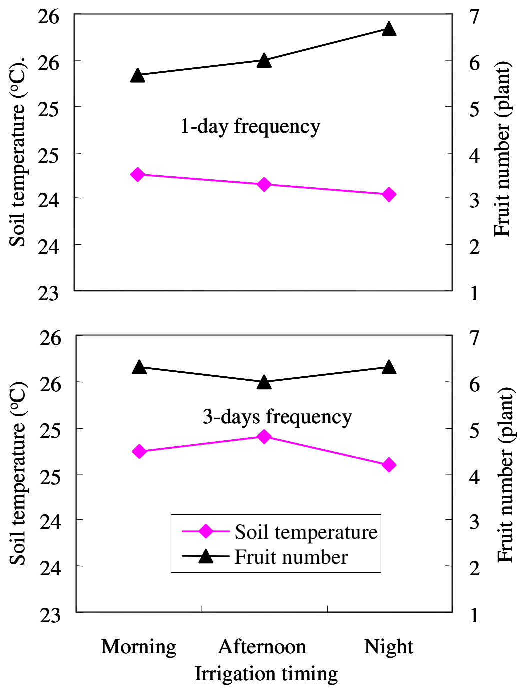

Figure 10 Effect of average soil temperatures and irrigation timing on tomato fruit numbers

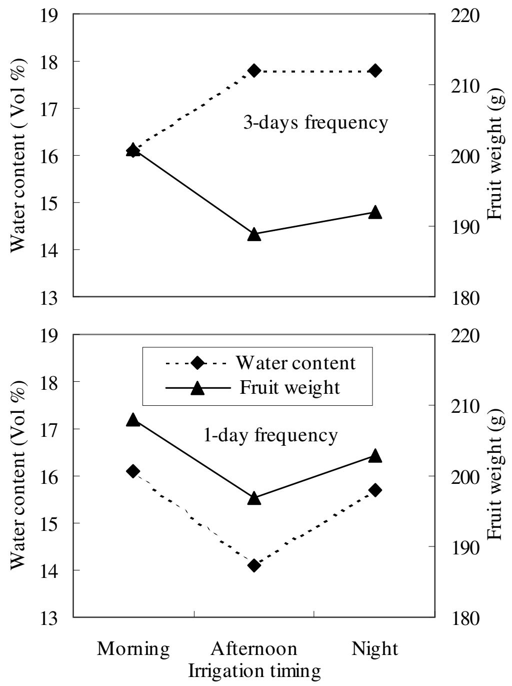

Figure 11 Effect of soil water content and irrigation timing on average fruit weights

4) Xylem water potential

Xylem water potential depend 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 increases under adequate water supply. Xylem water potential varied with water supply and therefore, it may be quite effective to monitor moisture stress in plants [4]. The trend was very clear in 3-days frequency, in which higher xylem water potential for all irrigation timings were found after irrigation where the soil water content was high. The high xylem water potential obtained at the first day after irrigation and it gradually decreased with decreasing soil water content until the irrigation event took place as clearly indicated on day 1 and day 5 in 3-days irrigation frequency (arrows in Fig. 6). A comparison of tomato yield (Fig. 2) with xylem water potential (Fig. 6) revealed that the high yield resulted in higher plant water stress and consequently, low xylem water potential. Increase the number of fruits in plants exert an additional pressure on roots to extract more water from soil in order to recover the requirement but the majority of extracted water diverted to fruit not to leaves and resulted in low xylem water potential.

5) Soil water content

The variation in soil water content as indicated in figure 7 was due to many factors. The low soil water content at the first stage of the growing season resulted from the little amount of water supply (250 ml when required). The applied amounts almost every two days moist only thin layer of soil surface, which easy to evaporate and result in a little effect on the change of soil water content. During the second stage, which shows higher soil water content, the Applications of irrigation treatments took place, the amount of applied water was also increased and the vegetative growth of the plant was developed. Due to the increase in water supply, much water was infiltrated and retained in soil profile and due to the developed of vegetative growth, the evaporation from soil was reduced. Both reasons resulted in high soil water content during second stage. Another indirect reason may also help to increase soil water content during second stage was the heavy rain outside of the greenhouse. The soil inside and outside the greenhouse is sandy loam soil characterized by higher conductivity (table 1). The isolated conditions in the greenhouse result in higher hydraulic gradient inside than outside of the greenhouse. Due to the differences in hydraulic gradient between inside and outside soils, the water flows horizontally form outside to inside and increase the soil water content of the subsurface soil, which resulted in high soil water content.

The reduction in soil water content during third stage was resulted from the increase in water depletion from the soil by plants due to the high demands of fruiting and evapotranspiration as a result of the hot summer weather. On the other hand the water supply remains constant at this stage; increase demand with constant water supply lead to much depletion from soil profile resulted in the reduction of soil water content. The higher soil water content in 3-days than in 1-day irrigation frequency was due to the amount of water supply. In 3-days frequency, much amount of water were supplied during irrigation event, as a result, much water was infiltrated and retained in soil profile, consequently less water evaporated form the soil surface result in high soil water content. But, less amount of water was supplied every day for 1-day frequency, infiltrated in thin surface soil layer and easily depleted by the plant use and the higher evaporation resulted in low soil water content.

The lower soil water content of the afternoon irrigation timing for 1-day frequency (Fig. 7) was mainly resulted from high evaporation demands because evaporation during mid day was very high compared to evaporation at early morning or at night. The water content of night irrigation was lower than that in early morning irrigation at the last growing stage for 1-day frequency (Fig. 7). These results may be due to the high yield of night irrigation compared to early morning irrigation, as indicated in figure 2. Increase the number of fruits in plants exert an additional pressure on roots to extract more water from soil in order to cover the requirements, resulted in low soil water content. The low soil water content of early morning irrigation for 3-days irrigation frequency may be due to the same reason.

The higher soil water content of the afternoon treatments during the first week of treatments application (Fig. 12) was due to technical problem. After applying irrigation treatments we discovered that the electrical valve of afternoon irrigation has a manufacture defect. Due to this defect too much water have been applied to the soil resulted in high water. Therefore, the electrical valve replaced with a new one and the irrigation for this treatment was stop until water content was controlled again.

6) Water use efficiency

The higher water use efficiency in root containers experiment was obtained from 5 days irrigation frequency. The water use efficiency obtained from the amount of water used to produce 1 g of dry matter. The 5-days irrigation frequency saves 18% and 12% of irrigation water compared to 1 and 3 days irrigation frequencies respectively. For tomato yield experiment in the greenhouse the higher water use efficiency obtained from early morning irrigation in 3-days frequency. 32.7 L of water was required to produce 1 kg tomato meanwhile 36 L of water was required to produce 1 kg of tomato for night irrigation in 1-day irrigation frequency (Fig. 9). This mean that, giving the same amount of water for all treatments, the early morning irrigation every 3 days increased water use efficiency by 11% – 20% compared to night and early irrigations of the 1-day frequency without effect on crop yield.

CONCLUSIONS

Irrigation frequencies and timings have large effect on root development, tomato yield, water distribution and water use efficiency. Increasing irrigation interval decreases roots dry weight. Decreasing in root system due to water stress resulted in a reduction in shoot dry weights. Water stressed conditions encourage tomato plants to developed their root systems in the deeper soil where soil moisture content was high. Increasing irrigation interval saved more water at early growing stage of the plants. The 5-days irrigation interval increased water use efficiency (amount of water required to produce 1 gram dry matter) by 18% and 12 % compared to 1 and 3 days frequencies respectively.

Irrigation at early morning every 3 days increased yield by 10 % over the highest yield of 1-day frequency. Irrigation at early morning every 3 days was the best irrigation timing because it increases the yield by 15 % and 14 % compared to afternoon and night irrigation respectively. For 1-day frequency irrigation at night was better than irrigation at early morning or afternoon because it increases the yield by 11 % and 3% compared to early morning and afternoon irrigation timings respectively. Less water supply and higher crop yield reduced the shoot and leaves dry weights and decreased xylem water potential. Applying irrigation water every 3 days increased the soil water content compared to every day frequency. Irrigation at afternoon for 1-day frequency decreased the soil water content compared to irrigation at early morning and at night. Variation of soil temperature was not clear due to the change in irrigation time or frequency. The behavior of soil temperature may be due to a combination of several factors such as soil water content, time of water application, root system and plant growth stage. Irrigation at early morning every 3 days increased water use efficiency compared to the other irrigation timings.

By applying the same amount of water for all treatments, the early morning irrigation of 3-days frequency increased the yield or water use efficiency by 11% - 20%

compared to night and early morning irrigation timings of 1-day irrigation frequency. In conclusion the early morning irrigation every 3-days was the best compared to all treatments and by choosing the proper irrigation frequency and timing efficient water use or higher yield can be obtained.

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