

Effect of rhizosphere cooling on tomato crop performance under controlled environment structure

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Abstract

In-house temperature build-ups under controlled environment structures can result in media moisture stress, photosynthetic reduction and serious plant wilting in crops, which are all factors that affect crop development. Research had been undertaken to explore cooling the rhizosphere of the plants instead of cooling this structure. A water chilling system delivers predetermined chilled water at 25, 20 or 15 °C through piping was developed to chill the root zone of tomato. This system can be adapted into existing controlled environment structures and fertigation systems with minor amendments. Research studies conducted showed that controlled chilling of the rhizosphere of tomato significantly increased the vegetative growth and yield of tomato. Chilling enhanced the vegetative growth with 7.4% longer plant length, 8.8% bigger stem diameter and 3.6% longer internodes and 1 – 13% more root volume. Tomato raised in chilled root zone was also found to have 11.8% more fruit number, 21.6% more fruit weight per plant, 3.3% heavier fruit weight and 22.7% higher yield than conventional method. During postharvest storage at 25 °C, root zone cooling showed significant ($p < 0.05$) effect on lightness, chroma, firmness and total soluble solids but did not affect hue and weight loss. However, at 8 °C storage, root zone cooling showed significant ($p < 0.05$) effect on chroma and ascorbic acid but not on lightness, hue, firmness, weight loss and TSS.

Keywords: in-house temperature, water chilling system, growing medium, root zone temperature, fruit quality

Introduction

Researchers have introduced and evaluated various aerial cooling methods like circulation fan, fine mist fogging and thermal screen to lower in-house air temperatures (Shen and Yu 2002; Sethi and Sharma 2007; Muhammad et al. 2011), so as to create conducive environments for cultivation of heat sensitive temperate

vegetables. Nevertheless, these aerial cooling systems are still insufficient to lower the in-house temperature to optimum level between 25 – 30 °C. Further research had been undertaken to explore the new technology of cooling the rhizosphere of the plants instead of cooling the aerial environment of the controlled environment structure. The control of root zone

Article history
Received: 10.10.2013
Accepted: 6.3.2015

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temperature is easier and more economical than that of other environmental factors such as air temperature and can be an effective solution to temperature stress (Moon et al. 2007).

Normal growth media temperature conditions in Malaysian lowlands usually vary between 27 – 30 °C (Mohammud et al. 2011). Research work by Moorby and Graves (1979) and Taber and Gansme (2001) indicated that soil temperature growth for tomato should be at least 15 – 30 °C for an increase in plant growth and to get the best fruit quality and yields. Many studies on root zone temperature manipulation had been done in the temperate countries (Kosobrukhov 1990; Dodd et al. 2000; He et al. 2001; Moon et al. 2007) but very little in tropical regions.

Leow (2006) had successfully grown temperate leafy vegetables in the hot-humid climate of Singapore using chilled fertigation technique via aeroponic system. A Malaysian commercial company, Sime Fresh Sdn. Bhd. had adapted a similar system for temperate leafy vegetable production at Labu-Seremban, Negeri Sembilan. Nevertheless, studies on the effects of root zone cooling in cocopeat-rice husk media systems are limited especially in Malaysian weather conditions.

In this project, a water chilling system through piping was developed to chill the root zone of tomato plant. This chilling system was adapted into existing controlled environment structure and fertigation systems with minor amendments to existing facilities. This research was based on a hypothesis that cooling the root zone of tomato to an optimum temperature will improve the tomato plant growth, fruit yield and quality.

Materials and methods

The study was conducted under a semi-mechanically controlled environment (CE) structure located at MARDI Headquarters, Serdang, Selangor, Malaysia with latitude 2°59'6"N and longitude 101°42'16"E. The

CE structure is a saw-toothed roof type with a gable span width of 6.4 m by 40 m long and consists of three bays (*Plate 1*). The height of the structure is 5.6 m. The roof and sidewalls are respectively covered with 200-micron transparent polyethylene film and 50 mesh insect-proof netting. The floor is covered with woven polyethylene sheet. The top and side vents were deployed for in-house ventilation. Three units of circulation fans were used to circulate the in-house air horizontally (*Plate 2*). High pressure-low volume fogging nozzles were installed to spray sufficient moisture into the CE structure. Thermal screens made of aluminised fibre netting were installed to provide 30 – 40% shading and to reflect light.

A water chilling system through 25 mm diameter stainless steel piping was developed to chill the root zone of tomato (*Plate 3*). The chilled water system consisted of a chiller barrel with condenser coil and condenser fan, compressor, chilled water pump, water tank and process cooling pump. All these components were placed in a chiller room which was located in front of the CE structure. The water chilling system delivered predetermined chilled water at 25, 20 or 15 °C, through pipe networks that passed through the rhizosphere of tomato. The planting system consisted of long polypropylene troughs of 30 cm width and 20 cm height containing a growth medium in the ratio of 7:3:2 cocopeat, burnt rice husk and perlite (by volume). Treatments consisted of rhizosphere cooling as follows: T1 = Root zone cooling at 25 °C; T2 = Root zone cooling at 20 °C; T3 = Root zone cooling at 15 °C; and T4 = Control.

Tomato variety Baccarat was used. Seedlings were raised in the nursery to be field planted after 25 days. Tomato seedlings were transplanted in the long troughs in two rows in a triangular pattern at 20 cm between rows and 60 cm between plants in the row (*Plate 4*). Nutrient solution was administrated to the plants using drip fertigation system four times a day. Nutrient



Plate 1. Controlled environmental structures at MARDI Headquarters, Serdang. The structures are covered with 200-micron transparent polyethylene and 50 mesh insect-proof netting. Top and side vents are part of natural ventilation system

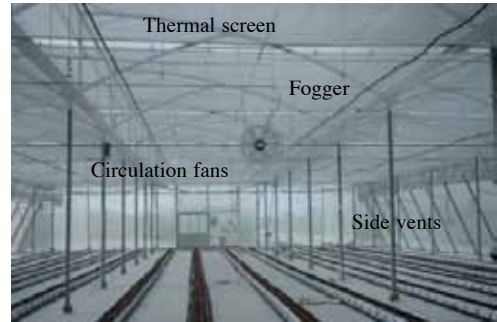


Plate 2. Circulation fans, fogging nozzles and thermal screen installed in the structure to control the in-house environment. The floor is covered with woven polyethylene sheet



Plate 3. (a) Two rows of 25 mm diameter stainless steel pipe used in root zone cooling. (b) Pipe network and solenoid valves installed for root zone cooling



Plate 4. Tomato trees were planted in 30 cm width by 20 cm height and 36 m long growing container

solution was prepared by dissolving a straight, highly soluble hydroponic grade fertiliser in the irrigation water. Treatment plots, each 36 m long, were arranged in a randomised complete block design with three replications. In-house environmental data such as air temperature and relative humidity data were collected using the 'Watchdog' sensors. While light intensity and carbon dioxide concentration level were collected using lux meter and carbon dioxide gas sensors respectively throughout the cropping season (6 months period). Crop data recordings were made 4 months after transplanting on plant length, stem diameter and internode length. Throughout the cropping season, samples were collected

for fruit number per plant, fruit weight per plant, average fruit weight and yield in tons per hectare. For postharvest fruit quality assessment [colour, firmness, weight loss, total soluble solids (TSS), ascorbic acid], tomatoes fruits were kept at ambient temperature (25 °C) over 16 days and storage at 8 °C for 4 weeks after harvest.

The weight loss of tomato sample was measured by the difference in weight before and after storage using weight machine. Changes of the colour of tomato fruit were measured using a Minolta CR-400 Chroma Meter (Minolta Corp., Osaka, Japan). The values of lightness, chroma and hue were taken randomly at three positions of a fruit. Lightness of the colour, ranges from 0 (dark) to 100 (white). The chroma values indicate the saturation of the colour on the surface of tomato fruit. The hue angle values of 0°, 90°, 180° and 270° correspond to the red, yellow, green and blue colour respectively.

The firmness of tomato fruits was measured using the texture analyser machine (model TA.XT.plux) with 5 mm needle attachment. Load cell of full scale ranges from 5 – 50 kg for penetration through the skin. The drive speed to determine the yield force used was 100 mm/min. The results of texture measurements were reported in Newton (N).

TSS were determined using a digital refractometer (model Atago, 0 – 32%) calibrated at room temperature and values were expressed in percentage. Juice from the flesh was dropped onto the prism and data taken. Ascorbic acid was determined according to Ranganna (1977) by dichlorophenol indophenol titration, reagent 3% metaphosphoric acid (HPO₃) to extract ascorbic acid, with L-ascorbic acid as a standard. The ascorbic acid content was calculated as follows:

$$\text{Ascorbic acid (mg/100 g)} = \frac{\text{titre} \times \text{dye factor} \times \text{volume made up} \times 100}{\text{aliquot used for extraction} \times \text{weight or volume of sample taken}}$$

Results and discussion

Air temperature, relative humidity, light intensity and carbon dioxide concentration inside the CE structure

The average air temperatures in CE structure during the study period ranged from 27.5 – 30.5 °C. These temperature ranges were slightly above optimum level of 25 – 30 °C. The average relative humidity was 77 – 87%, within a safe range of 70 – 90% (Von Zabeltitz 2011). The light intensity inside the structure was 1 – 3 kLux. Carbon dioxide concentration was high (700 – 1000 ppm), above as what is required by the plant (300 – 500 ppm) (Mat Sharif et al. 2008). The carbon dioxide concentration was high in the CE structure due to high air exchange rate between inside and outside air.

Plant length, stem diameter and internode length

Measurements on plant length showed that T1, T2 & T3 plants were significantly longer than T4 plants (*Table 1*). Average plant length from T1, T2 & T3 was 7.4% longer than T4 plants. No differences were observed between T1, T2 & T3. The results showed that lower root zone temperatures (15 – 20 °C) produced taller/longer plants but not significantly different from plants in 25 °C. A similar trend was observed by Leow (2006) on purple basil which had taller plant when root zone temperature maintained at 25 °C than 30 °C.

No differences were found in stem diameter among T1, T2 & T3, but these were significantly higher than in T4 plants. Average stem diameter from T1, T2 & T3 was 8.8% bigger than T4 plants.

Plants in lower root zone temperatures (T1, T2 & T3) also had 3.6% longer internodes than in T4. There were no differences in internode length among T1, T2 & T3, but these were higher than the internode length of T4. It was seen that root zone temperature of 25 °C produced taller/longer plants with bigger stem and longer internode.

Table 1. Effect of root zone cooling on plant length, stem diameter and internode length at 4 months after transplanting

Treatment	Plant length (m)	Stem diameter (mm)	Internode length (cm)
T1 – Root zone cooling at 25 °C	3.94a	11.9a	7.97a
T2 – Root zone cooling at 20 °C	3.99a	11.8a	8.03a
T3 – Root zone cooling at 15 °C	4.02a	11.8a	7.93a
T4 – Control	3.71b	10.9b	7.70b
Average (T1, T2 & T3) >T4	7.4%	8.8%	3.6%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

Table 2. Effect of root zone cooling on tomato root volume production (cm³) at various growth stages

Treatment	After transplanting		
	4 months	5 months	6 months
T1 – Root zone cooling at 25 °C	13.97a	4.10a	3.33a
T2 – Root zone cooling at 20 °C	13.71a	4.08a	3.07a
T3 – Root zone cooling at 15 °C	8.22a	3.41a	2.84a
T4 – Control	10.58a	3.82a	3.22a
Average (T1, T2 & T3) >T4	13.1%	1.1%	-4.3%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

Plant root volume

There were no significant differences in root volume at different treatments as shown in *Table 2*. However, T1 had the most roots and T3 had the least in all root zone cooling treatments throughout the plant growth. The root volume for T4 was slightly lower than the root volume of T1. Plants in lower root zone temperatures (T1, T2 & T3) had 13.1% and 1.1% more root volume than in T4 at 4 and 5 months after transplanting respectively. Feil et al. (1990) also discovered a similar trend in their work on temperate maize that crop grows better at 12 – 14 °C with more root dry matter. Root zone temperatures of 15, 20 and 25 °C influenced new root proliferation on Douglas-fir seedling. Greater rooting in lower root zone temperature were found in order to increase spring cold hardiness and thus, improve field performance (Jacobs et al. 2008). In a study by Psarras et al. (2000), a peak in new root emergence coincided partially with major phases of shoot and fruit growth of Mutsu apple trees. This

indirectly shows that more root volume will also indicate an increase in shoot and fruit growth. At lower root zone temperatures (15 – 25 °C) the plants were taller/ longer due to conducive and comfortable rhizosphere environment. Broccoli yield was also linearly related to both the vegetative top dry weight and root dry weight of mature plants (Díaz-Pérez 2009).

Fruit number and fruit weight

There was a significantly higher fruit number per plant in T1, T2 & T3 than in the control (*Table 3*). Average fruit number per plant from T1, T2 & T3 was 11.8% more than T4 plants. Fruit weight per plant in T1, T2 & T3 was also 21.6% higher than in T4. There were no differences in fruit number and fruit weight per plant between T1, T2 & T3, indicating that a root zone temperature at 25 °C was enough to produce high fruit number per plant and fruit weight per plant. Singh et al. (2012) found that lower root zone temperature as a result of 50% shading inside low tunnels increases

Table 3. Effect of root zone cooling on fruit number and fruit weight

Treatment	No/plant	Wt/plant (kg)
T1 – Root zone cooling at 25 °C	32.3a	3.594a
T2 – Root zone cooling at 20 °C	33.4a	3.737a
T3 – Root zone cooling at 15 °C	32.2a	3.769a
T4 – Control	29.2b	3.042b
Average (T1, T2 & T3) >T4	11.8%	21.6%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

Table 4. Effect of root zone cooling on average fruit weight and yield

Treatment	Weight (g)	Yield (t/ha)
T1 – Root zone cooling at 25 °C	105.5a	64.914a
T2 – Root zone cooling at 20 °C	105.7a	67.544a
T3 – Root zone cooling at 15 °C	104.1a	68.074a
T4 – Control	101.7b	54.495b
Average (T1, T2 & T3) >T4	3.3%	22.7%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

fruit number per plant and fruit weight of strawberries as compared to planting in the open field. Another possible reason of higher yield could be due to CO₂ enrichment under protected structure stimulating growth directly and finally increasing the number of flowers and fruit set which ultimately resulted in higher yield.

Average fruit weight and yield

Fruits in T1, T2 & T3 had similar average fruit weight, which was 3.3% higher than that in control (Table 4), indicating heavier fruits from plants in lower root zone temperatures. Yield was similar among T1, T2 & T3, and significantly higher than the yield in the control, again showing a root zone temperature at 25 °C was enough to produce high tomato yields. Moorby and Graves (1979) and Taber and Ganseme (2001) also revealed that soil temperature for tomato should be at least 15 – 30 °C for good plant growth and to get the best fruit quality and yields. Díaz-Pérez et al. (2007) stated that high root zone temperature resulted in reduced plant growth and yield

compared to plants grown at the optimal temperature of 26.1 °C which is more favourable to tomato plant growth. Root zone temperature of more than 27 °C causes stress, resulting in plants with lower vigour and fruit yield.

Postharvest fruit quality assessment 1 [tomatoes fruits were kept at ambient temperature (25 °C) over 16 days]

Fruit quality of tomato, in terms of colour (Table 5) showed that T3 reduced lightness, T2 and T3 reduced chroma (colour intensity), while there were no differences in hue (yellowish-orange). This indicated that root zone temperature did not affect the original yellowish-orange colour of tomato (hue) but significantly reduced intensity (chroma) at 15 – 20 °C and lightness of the fruits at 15 °C.

Keeping the fruits at ambient temperature of 25 °C showed that in terms of fruit firmness, values were significantly lower in T1 (Table 6), while there were no differences in weight loss, hue and ascorbic acid throughout 16 days. Lower root zone

Table 5. Effects of root zone cooling on postharvest quality (colour: lightness, chroma, hue) of tomato at ambient temperature (25 °C) over 16 days

Treatment	Lightness	Chroma	Hue
T1 – Root zone cooling at 25 °C	49.93ab	42.46a	63.22a
T2 – Root zone cooling at 20 °C	50.23a	41.03b	64.54a
T3 – Root zone cooling at 15 °C	48.77b	40.28b	62.34a
T4 – Control	50.39a	41.93a	64.08a
Average (T1, T2 & T3) >T4	-1.5%	-1.6%	-1.1%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

Table 6. Effects of root zone cooling on postharvest quality of tomato at ambient temperature (25 °C) over 16 days

Treatment	Firmness (N)	Weight loss (%)	TSS (°Brix)	Ascorbic acid (mg/100 g)
T1 – Root zone cooling at 25 °C	1.56b	0.24a	3.17ab	27.80a
T2 – Root zone cooling at 20 °C	1.74a	0.25a	3.13ab	28.20a
T3 – Root zone cooling at 15 °C	1.61ab	0.30a	3.28a	26.59a
T4 – Control	1.72a	0.34a	3.04b	26.99a
Average (T1, T2 & T3) >T4	-4.8%	-22.5%	5%	2%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

Table 7. Effects of root zone cooling on tomato fruit colour over storage at 8 °C

Treatment	Lightness	Chroma	Hue
T1 – Root zone cooling at 25 °C	46.30a	40.29b	59.81a
T2 – Root zone cooling at 20 °C	45.75a	42.38a	60.08a
T3 – Root zone cooling at 15 °C	45.34a	41.39ab	59.79a
T4 – Control	45.37a	42.16a	59.53a
Average (T1, T2 & T3) >T4	0.9%	-1.9%	0.6%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

temperatures resulted in higher TSS values (sweeter fruits).

Postharvest fruit quality assessment 2 (tomatoes fruits were kept at 8 °C for 4 weeks)

Postharvest quality of tomato under storage at 8 °C for 4 weeks showed no differences in lightness and hue (yellowish-orange) (Table 7). T1 significantly ($p < 0.05$) reduced chroma (colour intensity) of fruit.

There were also no differences in fruit firmness, weight loss and TSS during

storage over 4 weeks (Table 8). However, fruits from plants grown in lower root zone temperatures retained higher ascorbic acid (Vitamin C) content during storage.

Conclusion

Lower root zone temperatures of 20 – 15 °C would give taller/longer plants and higher overall yield than those in 25 °C, but the differences were not significant. Root zone cooling to a temperature of 25 °C would give taller/longer plants with bigger stem, longer internodes and more root volume.

Table 8. Effects of root zone cooling on postharvest quality of tomato over storage at 8 °C

Treatment	Firmness (N)	Weight loss (%)	TSS (°Brix)	Ascorbic acid (mg/100 g)
T1 – Root zone cooling at 25 °C	1.50a	0.18a	3.61a	14.28a
T2 – Root zone cooling at 20 °C	1.69a	0.21a	3.49a	13.56ab
T3 – Root zone cooling at 15 °C	1.65a	0.06a	3.62a	14.36a
T4 – Control.	1.65a	0.19a	3.62a	12.48b
Average (T1, T2 & T3) >T4	-2.2%	-21%	-1.3%	12.7%

Values in a column with the same letter are not significantly different at $p < 0.05$ according to the DMRT

Root zone temperature of 25 °C is enough to give higher fruit number per plant, fruit weight per plant, average fruit weight, and yield in t/ha. Plants grown in lower root zone temperatures also produce fruits with higher TSS values (sweeter), and higher ascorbic acid (vitamin C) content during storage at 8 °C. Research achievement in root zone cooling technology will create an interest for growers in the cultivation of high-value temperate crops such as tomato in the hot tropics.

Acknowledgments

The authors wish to express their gratitude to MOSTI for providing research grant and to MARDI for providing the facilities for this study. Special thanks to Mr Mohd Yusof Zun, Ms Norahshekin Abdul Rahman and Ms Siti Ashah Abdul Rahim for their assistance throughout the research work.

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Abstrak

Suhu dalaman yang meningkat di bawah struktur persekitaran terkawal boleh menyebabkan kekeringan medium, pengurangan fotosintesis dan tumbuhan layu dengan serius, ialah faktor yang mempengaruhi pertumbuhan tanaman. Penyelidikan telah dijalankan untuk menyejukkan zon akar tanaman dan bukannya penyejukan struktur ini. Satu sistem penyejukan membekalkan air sejuk pada suhu 25, 20 atau 15 °C melalui paip telah dibangunkan untuk menyejukkan zon akar tomato. Sistem ini boleh diguna pakai di dalam struktur persekitaran terkawal bersama sistem fertigasi dengan pengubahsuaian kecil. Kajian penyelidikan yang dijalankan menunjukkan bahawa penyejukan zon akar telah meningkatkan pertumbuhan vegetatif dan hasil tomato dengan ketara. Penyejukan telah meningkatkan pertumbuhan vegetatif dengan 7.4% lebih panjang tanaman, 8.8% lebih besar saiz batang dan 3.6% lebih panjang *internodes* dan 1 – 13% lebih besar isi padu akar. Tomato yang ditanam dengan zon akar yang disejukkan juga didapati mempunyai 11.8% lebih bilangan buah, 21.6% lebih berat buah setiap pokok, 3.3% lebih berat buah dan 22.7% lebih tinggi hasil berbanding dengan kaedah konvensional. Tiada perbezaan dalam kualiti buah dari segi warna, ketegangan dan kehilangan berat semasa penyimpanan, tetapi didapati memberi kesan terhadap jumlah pepejal larut (TSS) dan kandungan asid askorbik.