Growth, Yield, and Postharvest Attributes of Glasshouse Tomatoes Produced under Deficit Irrigation

Lucio U. Pulupol, M. Hossein Behboudian¹, and Keith J. Fisher

Department of Plant Science, Massey University, Palmerston North, New Zealand

Additional index words. *Lycopersicon esculentum*, mineral nutrition, respiration, ethylene evolution, ripening, color

Abstract. In glasshouse-grown tomatoes (*Lycopersicon esculentum* Mill. 'Virosa'), deficit irrigation (DI), in which plant water potential was allowed to decrease from -0.5 to -1.2 MPa, reduced plant growth and fruit yield, size and count, and caused blossom-end rot. Deficit-irrigated fruit had higher color intensity, lower water content, and higher concentration of sucrose, glucose, and fructose than well-watered (control) fruit. Fruit concentrations of Ca, Mg, and K were the same for both treatments on a dry weight basis, but they were higher in DI fruit than in control fruit on a fresh weight basis. Fruit gas exchange was measured for two 30-day-apart harvests. For both harvests, DI fruit produced higher quantities of CO₂ and ethylene than control fruit. Ethylene and CO₂ production peaks coincided for the first harvest in both treatments. In the second harvest, the CO₂ production peak preceded that of ethylene. Despite yield reduction, DI enhanced fruit desirability in terms of higher concentration of soluble sugars and higher color intensity.

Irrigation consumption is a major component of the water used for all purposes (Van Schilfhaarde, 1994). Deficit irrigation (DI) could help not only in reducing production costs, but also in conserving water and minimizing leaching of nutrients and pesticides into groundwater. In water-limiting production systems, establishment of DI as a management tool for tomatoes could be very effective in these respects because, as a popular vegetable, tomatoes are planted extensively throughout the world. However, before DI can be adopted as a management tool, its effect on fruit yield and quality should be examined.

So far, DI has been examined mainly for processing tomatoes. Irrigation with saline water, which creates a measure of water deficit in plants, also has been studied in conjunction with reduced irrigation in the glasshouse (Mitchell et al., 1991a) and in the field (Mitchell et al., 1991b). For the glasshouse study, neither water deficit nor salinity significantly affected total shoot dry weight. However, at final harvest, fruit fresh weight was decreased by 37% and 42% by water deficit and salinity, respectively. The corresponding decreases in fruit dry weight were 8% and 18%. Fruit hexose content was higher under both water and salt stress than in control. For the field experiment, Mitchell et al. (1991b) reported

that a moderate irrigation cutoff (50 days before harvest) or irrigation with saline water can significantly improve fruit quality, in terms of increasing total soluble solids concentration (TSS), without depressing marketable yields. A reduced water content and related increase in soluble solids concentration is desirable in processing tomatoes where paste production is the objective. The few studies conducted on the effects of irrigation amount and frequency on the quality of fresh-market tomatoes have included those on cracking (Abbott et al., 1985; Peet and Willits, 1995) and on TSS, pH, skin toughness, and titratable acidity (Tüzel et al., 1994). Provided an expected yield reduction is within acceptable limits and fruit quality is improved, DI could be an effective management tool for fresh-market tomatoes in the field and in protected cultivation systems.

Indeterminate glasshouse tomatoes, contrary to processing tomatoes, have excess foliage that usually has more photosynthetic area than the fruit needs (Rudich and Luchinsky, 1986). Photosynthesis and translocation are less sensitive to water stress than is growth (Kramer and Boyer, 1995). We, therefore, hypothesized that DI would not severely limit fruit yield in 'Virosa', which is an indeterminate cultivar, because photosynthates not used in vegetative growth might be used in fruit growth. Moreover, fruit quality could improve under DI, as has been shown for processing tomatoes (Mitchell et al., 1991b). Our objective was to characterize the responses of a fresh-market tomato cultivar to DI for plant growth, fruit quality, and yield. Fruit quality attributes studied included concentration of soluble sugars and mineral elements; and rate of ripening as characterized by color development, ethylene evolution, and respiration, which was measured as CO₂ production.

Eight-week-old 'Virosa' tomato plants were transplanted in July 1994 into 11-liter planter bags holding 100% bark containing (in kg·m⁻³): dolomite (3.0), agricultural lime (3.0), superphosphate (1.0), and iron sulfate (0.5). Plants were grown in a naturally-lit glasshouse with an average maximum/minimum of 28/18°C. Plants were trained with support strings, lateral shoots were removed weekly, and the tops were trimmed after 9 to 10 fruit trusses had developed. At anthesis, pollination was assisted by the daily use of a truss vibrator. Fertilization was practiced with each watering throughout the experiment using Cooper's (1979) complete nutrient solution.

There were two treatments: the control, which was watered four times a day, maintaining a midday average leaf water potential (Ψ) of about -0.5 MPa, and DI, which was watered when Ψ reached -1.0 to -1.2 MPa. Leaf water potential was monitored daily with a pressure chamber, using four replicate plants (one leaf from each plant) per treatment, at 0900 or 1200 HR and also at 1500 HR if Ψ in the DI treatment was approaching -1.0 MPa. A randomized complete-block design was used with four replications. Each replication consisted of two plots, each having 10 plants grown in a double row with 45 cm between the rows and 40 cm between plants within the row. A row of guard plants was grown around the experimental area. DI treatment started 64 days after sowing (DAS), 2 weeks following transplanting, when the first truss started to appear and continued up to the last harvest date.

At first anthesis, 16 plants per treatment (four plants per plot) were randomly tagged for monitoring crop development. The number of trusses and flowers present were recorded every 3 days. Fruit from 10 plants per plot (which included the tagged plants) were harvested twice a week from 10 Sept. to 3 Nov. 1994. Fruit were harvested when the blossom-end of the fruit turned orange (breaker stage), and were counted and weighed. Average fruit weight was approximated by dividing total fruit fresh weight by the total number of fruit harvested. The incidence of blossom-end rot (BER) was also recorded. At the final harvest, fresh and oven-dried weights (at 60°C for 4 days) of eight plants per treatment (two plants per plot) were measured.

At the first harvest, and 30 days later, 32 fruit per treatment (16 per harvest) were selected based on uniformity of size and color (breaker stage) for measurement of respiration and ethylene production. Ethylene and respiration were measured using gas chromatography for 10 consecutive days, starting from harvest, according to the procedure of Behboudian and Tod (1995). Color measurements (hue angle) were made at the side and blossom-end of the same fruit using a chromameter (CR-200; Minolta, Osaka, Japan). Hue angle ranges from 0° to 360°, with the green to red range encompassing $\approx 160^\circ$ to 20° (McGuire, 1992; Voss, 1992). In general, hue angle decreases as tomato fruit ripen. After the final color measurement, each fruit

Received for publication 19 Dec. 1995. Accepted for publication 4 June 1996. Mention of trade names does not constitute a guarantee or warranty of the products by Massey University, nor does it imply endorsement of similar commercial products. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

¹To whom reprint requests should be addressed.

was divided transversely into two halves. One half was weighed and oven-dried at 60°C for 4 days to provide a measurement of water content, then manually ground for measurement of mineral concentration. The other half was used for sugar analysis.

Concentration of fruit Ca, Mg, and K was determined following the procedure of Behboudian and Lai (1994), except that the atomic absorption spectrophotometer we used was a GBC 904AA (GBC Scientific Equipment Pty, Victoria, Australia). Concentrations of sucrose, glucose, and fructose were determined using high-performance liquid chromatography following the procedure of Behboudian and Tod (1995). Results of both mineral and sugar analysis were similar between the two harvests. They were therefore combined and are presented as means of 32 fruit per treatment. All data were tested using analysis of variance and *t* test with the Minitab statistical package (version 8.2; Minitab, State College, Pa.).

Results and Discussion

Whole-plant fresh and dry weights were higher in the controls than in DI plants (Table 1). The truss count for both treatments was similar early in the experiment, but the control plants developed more fruit trusses than DI plants beginning at 95 DAS (Fig. 1A). Similarly, more flowers with reflexed petals were present on the control plants (Fig. 1B). The fruit yield of DI plants was 39% that of control plants (Table 1) due to reductions in fruit count and weight. Fruit count, which includes the BER fruit, was reduced more (52% of controls) than fruit weight (75% of controls). Control fruit had higher water content than DI fruit. Tomatoes are most sensitive to water stress at flowering and fruit set (Helyes and Varga, 1994). Flowering and fruit set are continuous on indeterminate cultivars as new trusses develop. Therefore, stress during flowering and fruit set could not be avoided. Reduction with the DI treatment in fruit yield observed in this study would be unacceptable in horticultural systems where water is not a limiting factor in production. The level of DI tested, based on leaf Ψ of -1.0 to -1.2 MPa, required that DI plants be watered only on 29 days compared to 120 days for control plants throughout the course of the experiment. For both treatments, plants were watered four times per day, during their respective watering day, and Ψ in DI plants increased to the level of control plants the day after rewatering.

BER occurred solely in DI fruit from 108 to 145 DAS and affected only 0.9% of the total number of fruit harvested from this treatment. Calcium is transported through the transpiration stream (Tibbitts, 1979) and it is implicated in the BER incidence in tomato fruit (Barker and Ready, 1994). However, the BER incidence might have been due to the uneven distribution of Ca within DI fruit. There was no relation between total Ca concentration in fruit and BER incidence. Concentrations of Ca, Mg, and K were the same ($P \leq 0.05$) on a dry weight basis for both irrigation treatments. For Ca, Mg, and K, the concentrations on a dry weight basis (in $\text{mg}\cdot\text{kg}^{-1}$) were, respectively, 1180, 1900, and 3720 for the control fruit and 1020, 2060, and 3690 for the DI fruit. On a fresh weight basis, these concentrations were higher ($P \leq 0.05$ for Ca and $P \leq 0.01$ for Mg and for K) in DI fruit than in control fruit. For Ca, Mg, and K, the concentrations on a fresh weight basis (in $\text{mg}\cdot\text{kg}^{-1}$) were, respectively, 67, 211, and 107 for the control fruit and 90, 312, and 175 for the DI fruit. Barker and Ready (1994) also found no relationship between concentrations of Ca, Mg, and K in fruit and BER incidence. Measurement of Ca in different parts of the fruit might better identify areas in the fruit which have a Ca deficiency.

Concentrations of sucrose, fructose, and glucose were higher in DI fruit than in control fruit ($P \leq 0.01$). The values (in $\text{g}\cdot\text{kg}^{-1}$, fresh weight) for sucrose, fructose, and glucose in DI fruit were 0.78, 14.7, and 14.3, respectively. The corresponding values for control fruit were 0.18, 11.5, and 10.7. Mitchell et al. (1991b) observed that starch concentration early in fruit development was increased by water deficit and salinity. Water deficit causes the conversion of starch to sugar, and during water stress, carbohydrate metabolism is disturbed, often leading to accumulation of sugars (Kramer, 1983).

Deficit-irrigated fruit from both harvests produced higher quantities of CO_2 and ethylene compared to control fruit (Fig. 2). The difference was greater for the second harvest, when plants had been exposed to a longer duration of DI. Water stress is thought to increase respiration due to sugar accumulation (Kramer, 1983), which could have occurred in our experiment since the DI fruit had higher concentrations of soluble sugars than the control fruit. An increase in ethylene production from water-stressed tomato fruit was also observed by Basiouny et al. (1994), but the mechanisms were not stated. We did not study the mechanism involved or collect data to

evaluate the possible effect the higher ethylene production might have had on the shelf life of the DI fruit.

The fruit gas exchange data (Fig. 2) reflect the conflicting reports in the literature regarding the position of postharvest respiration and ethylene production peaks. Some authors have indicated that the respiratory rise in tomato fruit is in response to increased ethylene synthesis, which starts a chain of events leading to ripening (Hobson and Grierson, 1993). However, Saltveit (1993) found that in detached tomato fruit the respiration peak preceded the ethylene production peak, and he concluded that respiration in tomato may not be associated with climacteric ripening. Our data support this view (Fig. 2 B and D), while the coincidence in ethylene production and respiration peaks in Fig. 2 (A and C) does not necessarily indicate a cause-effect relationship.

Fruit color development, as reflected in changes of hue angle, followed a similar trend in both harvests for both treatments (Fig. 3). Color change was rapid in the first 4 to 5 days after harvest and nearly stopped thereafter. DI fruit had lower hue angle values than control fruit for the first harvest (Fig. 3A), which means they were redder than control fruit. Brecht et al. (1994) reported that water stress

Table 1. Effect of deficit irrigation (DI) on whole-plant weight and fruit characteristics of 'Viroso' tomatoes.

DI	Whole-plant wt (g/plant)		Fruit yield (kg/plant)	Fruit (no./plant)	Fruit wt (g)	Fruit water content (%)
	Fresh	Dry				
No	1098 ^z	115 ^z	2.32	40.7 ^y	57 ^y	94 ^x
Yes	584	75	0.90	21.2	43	91
Significance	**	**	**	**	**	*
DI as percentage of control	53	65	39	52	75	97

^zMeans of eight replicate plants per treatment.

^yMeans of 40 replicate plants per treatment.

^xMeans of 32 replicate fruit per treatment, 16 from the first and 16 from the second harvest.

**, *Significant at $P \leq 0.05$ or 0.01, respectively.

Fig. 1. (A) Mean number of trusses per plant and (B) mean number of flowers with reflexed petals per plant in 'Viroso' tomato as affected by deficit irrigation. Separate bars are the pooled SE of means. Each mean is based on 16 replicate plants per treatment.

improved fruit color in two experiments using drip irrigation and polyethylene mulch. Similarly, Rudich et al. (1977) found that DI tomato fruit had higher color intensity than well-irrigated fruit. Ethylene increases carotenoid concentration of the tomato fruit (Paz et al., 1982), with peak lycopene formation coinciding with peak ethylene production (Ishida et al., 1993). Therefore, the redder color of the DI fruit (Fig. 3) may have been a result of the higher ethylene production of these fruit (Fig. 2 A and B). Even if a cause-effect relationship does not exist between ethylene production and carotenoid synthesis, ethylene promotes ripening, which brings about lycopene accumulation.

This study showed that DI tomatoes could produce a crop when container-grown with a 0.7 MPa reduction in Ψ compared to well-

watered plants. Contrary to our hypothesis, DI resulted in a greater decrease in fruit yield than in vegetative growth (Table 1), apparently because of the sensitivity of flower truss formation to DI as discussed above, and also due to the fact that some vegetative growth was already completed at the time DI was imposed. In areas where water is either limited or expensive, the lower cost of fertigation may compensate for the yield reduction. Improvement in some fruit quality attributes could also be realized under reduced watering, which could result in a price premium if a niche market was created. A possibility for obtaining a higher yield than reported here for DI greenhouse-grown tomato plants is to apply a milder water stress than used in this study with an improvement in fruit quality still expected.

Fig. 2. Effect of deficit irrigation on (A and B) postharvest ethylene evolution and (C and D) respiration in 'Viroso' tomato fruit. Separate bars are the pooled SE of means. Each mean is based on 16 replicate fruit per treatment.

Literature Cited

- Abbott, J.D., M.M. Peet, D.H. Willits, and R.E. Gough. 1985. Water management of greenhouse tomatoes. *HortScience* 20:688-690.
- Barker, A.V. and K.M. Ready. 1994. Ethylene evolution by tomatoes stressed by ammonium nutrition. *J. Amer. Soc. Hort. Sci.* 119:706-710.
- Basiouny, F.M., K. Basiouny, and M. Maloney. 1994. Influence of water stress on the abscisic acid and ethylene production in tomato under different PAR levels. *J. Hort. Sci.* 69:535-541.
- Behboudian, M.H. and R. Lai. 1994. Carbon dioxide enrichment in 'Viroso' tomato plants: Responses to enrichment duration and to temperature. *HortScience* 29:1456-1459.
- Behboudian, M.H. and C. Tod. 1995. Postharvest attributes of 'Viroso' tomato fruit produced in an enriched carbon dioxide environment. *HortScience* 30:490-491.
- Brecht, J.K., S.J. Locascio, and K.A. Bergsma. 1994. Water quantity affects quality of drip-irrigated tomato fruit. *HortScience* 29:154-160.
- Cooper, A. 1979. The ABC of NFT: Nutrient film technique. Grower Books, London.
- Helyes, L. and G. Varga. 1994. Irrigation demand of tomato according to the results of three decades. *Acta Hort.* 376:323-328.
- Hobson, G. and D. Grierson. 1993. Tomato, p. 405-443. In: G. Seymour and G. Tucker (eds.). *Biochemistry of fruit ripening*. Chapman and Hall, London.
- Ishida, B.K., E.A. Balwin, R.G. Buttery, S.H. Chui, and L.C. Ling. 1993. Flavor volatiles, sugars and color development in ripening in vitro-cultured tomato fruit and calyx. *Physiol. Plant.* 89:861-867.

Fig. 3. Effect of deficit irrigation on fruit color in terms of hue angle in 'Viroso' tomato fruit. Separate bars are the pooled SE of means. Each mean is based on 16 replicate fruit per treatment.

- Kramer, P.J. 1983. Water relations of plants. Academic, London.
- Kramer, P.J. and J.S. Boyer. 1995. Water relations of plants and soils. Academic, San Diego.
- McGuire, R.G. 1992. Reporting of objective color measurements. *HortScience* 27:1254–1255.
- Mitchell, J.P., C. Shennan, and S.R. Grattan. 1991a. Developmental changes in tomato fruit composition in response to water deficit and salinity. *Physiol. Plant.* 83:177–185.
- Mitchell, J.P., C. Shennan, S.R. Grattan, and D.M. May. 1991b. Tomato yields and quality under water deficit and salinity. *J. Amer. Soc. Hort. Sci.* 116:215–221.
- Paz, O., H.W. Janes, B.A. Prevost, and C. Frenkel. 1982. Enhancement of fruit sensory quality by post-harvest applications of acetaldehyde and ethanol. *J. Food Sci.* 47:270–273.
- Peet, M.M. and D.H. Willits. 1995. Role of excess water in tomato fruit cracking. *HortScience* 30:65–68.
- Rudich, J., D. Kalmar, C.C. Geizenberg, and S. Harsel. 1977. Low water tension in defined growth stages of processing tomato plants and their effects on yield and quality. *J. Hort. Sci.* 52:391–399.
- Rudich, J. and U. Luchinsky. 1986. Water economy, p. 335–367. In: J.G. Atherton and J. Rudich (eds.). *The tomato crop: A scientific basis for improvement*. Chapman and Hall, London.
- Saltveit, M.E., Jr. 1993. Internal carbon dioxide and ethylene levels in ripening tomato fruit attached to or detached from the plant. *Physiol. Plant.* 89:204–210.
- Tibbitts, T.W. 1979. Humidity and plants. *BioScience* 29:358–363.
- Tüzel, Y., M.A. Ul, and I.H. Tüzel. 1994. Effects of different irrigation intervals and rates on spring season glasshouse tomato production. II. Fruit quality. *Acta Hort.* 366:389–396.
- Van Schilfgaarde, J. 1994. Irrigation—A blessing or a curse. *Agr. Water Mgmt.* 25:203–219.
- Voss, D.H. 1992. Relating colorimeter measurement of plant color to the *Royal Horticultural Society Colour Chart*. *HortScience* 27:1256–1260.