Effect of Arbuscular Mycorrhiza and Temperature Control on Plant Growth, Yield, and Mineral Content of Tomato Plants Grown Hydroponically

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Abstract. Mycorrhizal inoculation improves nutrient uptake in a range of host plants. Insufficient nutrient uptake by plants grown hydroponically is of major environmental and economic concern. Tomato seedlings, therefore, were treated with a mycorrhizal inoculant (Mycoroot™) at transplanting to potentially enhance nutrient uptake by the plant. Then seedlings were transferred to either a temperature-controlled (TC) or a non-temperature-controlled (NTC) tunnel and maintained using the recommended (100%) or a reduced (75% and 50%) nutrient concentration. Plants grown in the NTC tunnel had significantly poorer plant growth, lower fruit mineral concentration, and lower yield compared with fruit from plants in the TC tunnel. Leaves from plants in the NTC tunnel had higher microelement concentrations than those in the TC tunnel. Highest yields were obtained from plants fertigated with 75% of the recommended nutrient concentration, and not from the 100% nutrient concentration. Application of arbuscular mycorrhizal fungi (AMF) neither enhanced plant growth, nor yield, nor fruit mineral nutrient concentrations. However, temperature control positively affected the fruit Mn and Zn concentration in the TC tunnel following AMF application.

Protected soilless cultivation of fresh-market tomatoes has gained popularity in recent years due to improved plant growth, yield and fruit quality, although open field cultivation is still the preferred method of tomato production in South Africa (Maboko et al., 2009; 2011a). There is, however, a worldwide increase in the use of soilless production systems for vegetables (Raviv and Lieth, 2008) as typical field-based systems often result in disease built-up, making soil a less suitable cultivation medium. The recent more common occurrence of unfavor-

able weather conditions such as large rainfall and temperature fluctuations have resulted in the search for other means to optimize yield and quality of tomatoes. Amongst these is the use of soilless production systems under protection (Maboko et al., 2011b).

The optimal air temperature for growing tomato plants ranges from 18 to 28 °C, with the maximum air temperature at 30 °C (Saeed et al., 2007). Iwahori et al. (1963) indicated that frequent air temperatures above 30 °C in greenhouses during summer result in leaf scorch, low fruit set and production of small fruit. This is particularly important in tomato, where temperature is the most vital environmental factor influencing vegetative growth of the plant, from the initial seedling stage to flower formation and fruit development (Rylski, 1979; Roh and Hong, 2007; Saeed et al., 2007).

Tomato production in tunnels has gained popularity in South Africa due to improved plant growth, yield and quality under such systems (Maboko et al., 2009). The majority

of tunnel production in South Africa and in many other Mediterranean and not typically temperate climate countries is still carried out in NTC tunnels, whereas the use of TC tunnels is increasing steadily. Some producers still prefer NTC tunnels because of their lower cost and greater simplicity, relying on natural ventilation to reduce heat buildup inside (Perdigones et al., 2005; Maboko et al., 2012).

Arbuscular mycorrhizal fungi (AMF) grow in close association with plant roots, and play an important symbiotic role in the uptake and transfer of water and nutrients by the root system; in exchange, the plant supplies the fungi with sugars. The hyphae of AMF penetrate roots and grow extensively between and within living cortical cells, forming a very large and dynamic interface between symbionts (Farahani et al., 2008).

Mycorrhizae are known to increase plant growth, yield, and quality in high salinity soils (Mouk and Ishii, 2006), improve water and nutrient uptake (Farahani et al., 2008), increase resistance to pathogens such as *Alternaria solani* (Fritz and Jakobsen, 2006), and to lessen abiotic stress factors (Mouk and Ishii, 2006). This can result in reduced water stress, especially if accompanied by high air temperatures, a common scenario under protected cultivation. Mycorrhizae particularly enhance P uptake but can also increase NH_4^+ and NO_3^- uptake (Frey and Schüepp, 1993; Johansen et al., 1993), as well as the uptake of other nutrients, including Zn, Cu, and K (Marschner and Dell, 1994). For these reasons, mycorrhizae can play an important role in agricultural production by creating the possibility to enhance absorption of nutrients; thereby the amount of fertilizer required in hydroponic production systems could be reduced. This is particularly important as the concentration of minerals in the nutrient solution is a key factor in the improvement of tomato fruit quality, affecting fruit soluble sugars, acids, and minerals, as well as fruit flavor, shelf life, and color (Dorais et al., 2001).

Under soilless cultivation, the use of AMF has been reported for pepper (Ikiz et al., 2009) and tomato (Dasgan et al., 2008) with the intention to promote plant growth and, potentially, increasing yield and quality. The potential of AMF in soilless growing systems to reduce the nutrient concentrations applied has not been investigated previously. This study, therefore, investigates if AMF can colonize tomato plants grown in hydroponic fertigation systems and enhance nutrient uptake, thereby reducing the amount of fertilizer required to produce high quality fruit under TC and NTC conditions.

Materials and Methods

Application of treatments. Two experiments were conducted over the summer season (2009/2010) in an NTC and a TC tunnel at the Agricultural Research Council—Vegetable and Ornamental Plant Institute (ARC-VOPI), Roo-deplaat, South Africa (25°59' S; 28°35' E, at an altitude of 1200 masl).

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Table 1. Amount of fertilizer supplied ($\text{g}\cdot\text{L}^{-1}$) by different fertigation treatments at different stages of tomato plant development.

Application time	Fertilizer ($\text{g}\cdot\text{L}^{-1}$)	F1 (100% nutrient concn)	F2 (75% nutrient concn)	F3 (50% nutrient concn)
Planting to first flower truss	Hygroponic®	1.0	0.75	0.5
	$\text{Ca}(\text{NO}_3)_2$	0.8	0.6	0.4
First flower truss to third flower truss	Hygroponic®	1.2	0.9	0.6
	$\text{Ca}(\text{NO}_3)_2$	0.5	0.375	0.25
Third flower truss to end	Hygroponic®	1.2	0.9	0.6
	$\text{Ca}(\text{NO}_3)_2$	0.8	0.6	0.4
	KNO_3	0.3	0.225	0.15

Fig. 1. (A) Temperature-controlled tunnel. (B) Non-temperature-controlled tunnel.

Five-week-old tomato seedlings (fresh market cultivar FA593) produced from 200-cavity seedling trays using Hygroponic® as a growing medium, were transplanted into 10-L plastic bags containing sawdust as a growing medium. Transplants were inoculated with mycorrhiza by placing a teaspoon (7 g) of Mycoroot™ granules into the planting holes; then one seedling was placed into the hole. About 100 propagules, with a minimum of 10 spores per gram comprising four AMF species, *Glomus etunicatum*, *Paraglomus occultum*, *Glomus clarum*, and *Glomus mosseae* are contained in 1 g Mycoroot™. The composition and chemical concentration of fertilizers used for tomato production were Hygroponic® comprising N ($68 \text{ mg}\cdot\text{kg}^{-1}$), P ($42 \text{ mg}\cdot\text{kg}^{-1}$), K ($208 \text{ mg}\cdot\text{kg}^{-1}$), Mg ($30 \text{ mg}\cdot\text{kg}^{-1}$), S ($64 \text{ mg}\cdot\text{kg}^{-1}$), Fe ($1.254 \text{ mg}\cdot\text{kg}^{-1}$), Cu ($0.022 \text{ mg}\cdot\text{kg}^{-1}$), Zn ($0.149 \text{ mg}\cdot\text{kg}^{-1}$), Mn ($0.299 \text{ mg}\cdot\text{kg}^{-1}$), B ($0.373 \text{ mg}\cdot\text{kg}^{-1}$), and Mo ($0.037 \text{ mg}\cdot\text{kg}^{-1}$); calcium nitrate [$\text{Ca}(\text{NO}_3)_2$] comprising N ($117 \text{ mg}\cdot\text{kg}^{-1}$) and Ca ($166 \text{ mg}\cdot\text{kg}^{-1}$); and potassium nitrate (KNO_3) comprising K ($38.6 \text{ mg}\cdot\text{kg}^{-1}$) and N ($13.8 \text{ mg}\cdot\text{kg}^{-1}$). Plants were subjected to three fertigation treatments (Table 1), i.e., the recommended fertilization rate (100%) or reduced (75% and 50%) nutrient concentrations.

Treatments were applied either in a TC plastic tunnel equipped with two fans (1.1 kW fan, 1300-mm diameter) and a pad cooling system (Fig. 1A), or in an NTC tunnel (Fig. 1B) that relied on natural ventilation by means of a flap and door system that could be opened on each side. The $10 \text{ m} \times 30 \text{ m}$ (width $\times$ length) tunnels were covered with a 200- μm light diffusive plastic (Evadek Green Tint) and 200- μm white plastic was placed on the floor. Plants were kept at a plant population density of 2.5 plants per m^2 . There were 17 plants in each replicate per treatment, consisting of the three fertigation and two mycorrhiza treatments maintained under NTC or TC conditions. Plants in both experimental tunnels were trained to a single stem by twisting trellis twine around the main stem, fixing it to a stray wire 2 m away from the ground to support the plant. Side branches were removed weekly to maintain a single stem system. When plants had reached the horizontal wire at a height of 2 m (7–8 trusses), the growing point was removed to stop vertical plant growth.

The pH of the nutrient solution was measured on a daily basis with a handheld ‘HANNA’ EC and pH meter (HANNA Instruments, Mauritius), and maintained between pH 5.5 and 6.5 using nitric acid.

Maximum, minimum, and average monthly ambient temperatures for the experimental sites during the experimental period were measured using Tinyview data loggers [Gemini data loggers (UK) Ltd, Chichester]. These data loggers were placed at a height of 1.5 m and covered with a Stevenson-type screen ACS-500.

Plant growth and productivity measurements. Plant height, stem diameter (30 cm below the growing point), leaf number, leaf length (mm), and leaf width (mm) of four tomato plants per replicate per treatment were measured and recorded from four weeks after transplanting on a fortnightly basis until plants reached a height of 2 m. Fruit were harvested weekly at the breaker stage (Jones, 2008) from December to February. Yield data were collected from 10 plants per treatment, and the performance of the treatments was evaluated using total yield, marketable and unmarketable fruit, as well as physiological disorders as parameters. All harvested fruit, excluding unmarketable fruit (fruit exhibiting cracking or falling into the extra small size category of less than a diameter of 40 mm) (Maboko et al., 2011a), were graded into classes according to fruit diameter,

namely extra large ($>70 \text{ mm}$), large (60–70 mm), medium (50–60 mm), small (40–50 mm), and extra small ($<40 \text{ mm}$) using Vernier calipers.

Leaf analysis. The fourth leaf from the growing point of four plants per replicate per treatment was selected (Maboko et al., 2013) to determine the leaf N, P, K, Ca, Mg, Mn, Zn, B, Cu, and Fe concentrations. These leaves were oven-dried at 70°C for 48 h and ground using a mill with a 1-mm sieve. Nitrogen was determined on dry milled material using a Carlo Erba NA 1500 C/N/S Analyzer (Thermo Scientific). An aliquot of the digest solution was used for ICP-OES (Inductively coupled plasma optical emission spectrometry) for determination of Ca, Mg, P, K, Fe, Zn, Mn, and Cu concentration (Liberty Series II Model; Varian). All nutrient concentrations were expressed on a dry mass basis.

Fruit nutrient analysis. Four ripe medium-sized fruit were harvested from the fifth truss of four plants per replicate per treatment for nutrient analysis (P, K, Ca, Mg, Mn, Zn, B, Cu, and Fe), as described above. Nutrient concentrations were expressed per gram fruit dry mass.

Mycorrhiza colonization. At the end of the experiment, two plants per replicate per treatment (8 plants) were used to determine the percentage of AMF colonization. Roots were rinsed carefully with tap water in preparation for the assessment of mycorrhizal colonization. The root clearing and staining procedure were performed according to Koske and Gemma (1989) and percentage mycorrhiza colonization calculated as the number of 10-mm-long root segments out of 100 identified as colonized under a microscope at a $20\times$ magnification (Giovannetti and Mosse, 1980).

Statistical procedures. A randomized complete block design was used for each of the two tunnel facilities (TC and NTC). The treatment design for each experiment was a 3×2 factorial, with the two factors [three fertigation treatments, i.e., 100%, 75%, and 50% nutrient concentration; and two mycorrhiza treatments, i.e., mycorrhiza inoculation (+) and no inoculation (–)] randomized within each of the four block replicates. When data were collected over time as repeated measurements the time factor was included as a subplot factor in the analysis of variance (ANOVA) (Little and Hills, 1972).

Data of the two systems was tested for homogeneity of variances using Levene’s test (John and Quenouille, 1977). In cases where the variability in the observations of the two systems was of comparable magnitude, an analysis of the two systems’ observations together could be validly carried out. In cases where there was strong evidence against homogeneity a weighted ANOVA of the two systems combined was carried out using the inverse of the pooled variances of each system as weights (John and Quenouille, 1977). The Shapiro–Wilk test was performed to test for normality (Shapiro and Wilk, 1965). Student’s *t*-least significant differences (LSDs) were calculated at the 5% level to compare

Fig. 2. Percentage mycorrhiza colonization of tomato plants supplied with decreasing fertigation levels in TC and NTC. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1+, F2+, and F3+ indicate plants inoculated with mycorrhiza and fertigated with 100%, 75%, and 50% of the recommended nutrient concentration, respectively. LSD, least significant difference; ns, not significant.

Table 2. Effect of production system, nutrient concentration, mycorrhiza inoculation and number of days after transplanting (DAT) on tomato plant growth parameters.

Production system	Stem diam (mm)	Plant ht (mm)	Number of leaves/plant	Leaf length (mm)	Leaf width (mm)
NTC	12.74	1515.8 a	17.30	321.3 b	254.0 b
TC	14.11	1443.8 b	16.79	357.7 a	297.1 a
LSD _{0.05}	NS	51.20	NS	4.99	15.09
<i>Nutrient concentration/fertigation</i>					
F1	13.28 b	1490.6	17.09	344.8 a	280.8 a
F2	14.00 a	1479.2	17.18	345.8 a	283.1 a
F3	12.99 b	1469.7	16.87	328.0 b	262.8 b
LSD _{0.05}	0.586	NS	NS	10.05	10.38
<i>Mycorrhiza inoculation</i>					
+AMF	13.36	1490.0	17.3	339.5	274.8
-AMF	13.48	1469.6	16.8	339.6	276.3
LSD _{0.05}	NS	NS	NS	NS	NS
<i>Number of DAT</i>					
28	12.34 c	743.0 a	12.12 c	277.1 c	218.3 c
42	13.57 b	1128.6 b	12.84 c	338.1 b	283.7 b
56	12.72 c	1588.3 c	17.56 b	337.4 b	285.0 b
70	14.04 ab	1940.7 d	21.02 a	370.4 a	299.5 a
84	14.45 a	1998.5 e	21.68 a	374.7 a	291.3 ab
LSD _{0.05}	0.706	51.20	0.902	6.54	9.49

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100; F2, 75; F3, 50% nutrient concentration; +AMF, plants inoculated with mycorrhiza; -AMF, plants without mycorrhiza; ns, not significant; LSD, least significant difference.

Table 3. Effect of production tunnel system, fertigation level, and mycorrhiza treatment on tomato yield and physiological disorders per plant.

Production System	Marketable yield (g/plant)	Number of marketable fruit	Total yield (g/plant)	Fruit cracking		Catface	
				Number	Mass (g)	Number	Mass (g)
NTC	2508 b	25.5 b	3815 b	10.59 a	1051 a	0.1	9.8
TC	6039 a	45.5 a	6648 a	3.38 b	426 b	0.07	8.8
LSD _{0.05}	318.1	2.32	308.7	1.44	147.4	ns	ns
<i>Nutrient concentration/fertigation</i>							
F1	4130	35.01	5098 b	6.74	720	0.03	6.3
F2	4538	37.07	5593 a	8.16	846	0.13	12.7
F3	4151	34.46	5004 b	6.05	648	0.09	8.9
LSD _{0.05}	NS	NS	378.1	NS	NS	NS	NS
<i>Mycorrhiza inoculation</i>							
+AMF	4203	34.37	5242	7.88 a	830 a	0.06	9.0
-AMF	4344	36.67	5222	6.08 b	646 b	0.10	9.6
LSD _{0.05}	NS	NS	NS	1.44	147.4	NS	NS

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100; F2, 75; F3, 50% nutrient concentration; +AMF, plants inoculated with mycorrhiza; -AMF, plants without mycorrhiza inoculation; ns, not significant; LSD, least significant difference.

treatment means for significant effects including interactions. All analyses were performed using *GenStat*® version 11.1 (Payne et al., 2008).

Results

Mycorrhizal colonization. Percentage mycorrhiza colonization only showed a tendency to be higher in TC than NTC (Fig. 2). With a reduction in nutrient concentration from 100% (F1) to 75% (F2) to 50% (F3) of the recommended rate, a tendency of higher mycorrhiza colonization was observed (Fig. 2). Although AMF root colonization occurred following inoculation, no effect of such colonization on vegetative growth and tomato yield could be observed (Tables 2 and 3).

Effect of fertigation. Plants fertigated with F2 developed significantly thicker stems than those supplied with F1 and F3 (Table 2). Fertigation also affected leaf length and width; plants supplied with the higher nutrient concentrations had longer and wider leaves than those of F3 (Table 2). Leaves of plants fertigated with F3 were significantly narrower than those of plants supplied with F1 (Fig. 3); whereas after 56 to 84 days after transplanting (DAT), leaf width was similar in all the fertigation treatments with the lowest nutrient concentration tending to produce narrow leaves.

Interaction effects of production system and number of DAT on vegetative plant growth characteristics. Most vegetative growth parameters were affected by the interaction between production system and DAT (Figs. 4–8). Generally, plants grown under TC conditions had a wider stem than those grown under NTC conditions (Fig. 4). Stems were significantly thicker under TC conditions 42 and 56 DAT, although they did not differ significantly from those of plants grown under NTC conditions 70 and 84 DAT.

A significant increase in plant height was observed 42, 56, and 70 DAT for plants grown in the NTC tunnel compared with the TC tunnel (Fig. 5). Most plants reached a height of 2 m 70 DAT when their growing point was removed and, therefore, no further increase in plant height could be recorded beyond 84 DAT.

Leaf production on plants grown under NTC conditions was faster than on those grown under TC conditions, with a significantly greater number of leaves produced under NTC than under TC conditions 42 and 56 DAT (Fig. 6). Leaf length was significantly and positively affected by controlling the tunnel environment, with longer and wider leaves in TC than in NTC throughout the growing season (Figs. 7 and 8).

Tomato fruit and leaf nutrient content. Tomato fruit from plants grown under TC conditions contained a higher moisture percentage than fruit from plants grown under NTC conditions (Table 4). The production system also influenced fruit mineral content, with TC conditions significantly improving fruit macro- and microelement concentrations (Table 4).

Fig. 3. Effects of nutrient concentration and DAT on tomato leaf width. Recommended nutrient concentrations are 100%, 75%, and 50% for F1, F2, and F3, respectively; LSD, least significant difference.

Fig. 4. Interaction effect of production system and DAT on stem diameter. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; LSD, least significant difference.

Fig. 5. Interaction effects of production system and DAT on plant height. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; LSD, least significant difference.

Fig. 6. Interaction effects on production system and DAT on number of leaves. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; LSD, least significant difference.

Fruit from plants fertigated with F1 and F2 had a significantly higher P concentration than those from plants grown under F3 (Table 4). The Mn concentration of fruit from plants fertigated with the lower F2 and F3 concentrations was significantly lower than that from those maintained at the recommended concentration. Plants under full fertigation also produced fruit with a higher Zn concentration than those under F3, although not significantly different from those under F2. Plants inoculated with mycorrhiza bore fruit that contained a significantly lower P concentration compared with fruit from plants not treated with mycorrhiza. Even though the P concentration in tomato fruit grown under F3 was low, inoculation of plants with mycorrhiza did not significantly increase this P concentration (Fig. 9). Plants without mycorrhiza tended to contain higher leaf P concentrations than mycorrhiza inoculated plants grown under 100% and 75% nutrient concentration.

There was a significant interaction effect of production system and fertigation (Fig. 10) on fruit Mn concentration. Plants grown under TC conditions and fertigated with the full nutrient concentration produced fruit with the highest Mn concentration. Compared with NTC conditions, TC conditions produced tomato fruit with a higher Mn concentration independent of fertigation regime. Plants fertigated with 50% of the recommended rate (F3) under TC conditions performed similar to those fertigated at F1 (100% recommended fertigation) under NTC conditions. When inoculated with mycorrhiza, plants grown under TC conditions produced fruit that had a significantly higher Mn and Zn concentration than plants grown under NTC conditions, independent of mycorrhiza inoculation (Table 5).

Leaf nutrient concentration was significantly affected by the production system; the micronutrient concentrations of leaves from plants grown under TC conditions (Table 6) were lower than those under NTC conditions; the macronutrient concentrations, however, were higher under the TC than under the NTC environment. Most macroelements (N, P, K, Ca) were present in leaves in higher concentrations when plants were grown in the TC tunnel, while leaves of plants under NTC conditions had significantly higher Fe, Zn, and Mg concentrations. Although there was an increase in leaf N, P, and K with an increase in nutrient concentration (Table 6), the fertigation level did not affect Cu, B, Mn, Fe, Zn, and Ca leaf concentrations. A significant increase in Mg was observed when plants were fertigated with fertilizer levels (F2 and F3) lower than the recommended rate (F1). Application of mycorrhiza had no significant effect on any of the minerals analyzed in tomato leaf tissue.

Leaf Fe and Zn concentrations were unaffected by nutrient levels in the NTC tunnel; however, when grown under TC conditions, generally lower leaf Fe and Zn concentrations were observed when plants were supplied with less fertilizer (Table 7).

Tomato yield. Marketable yield, total yield, and number of marketable fruit were significantly higher from plants grown under TC than NTC conditions (Table 3). Surprisingly, marketable yield and number of marketable fruit were not significantly affected by fertigation level; however, plants fertigated with 75% of the recommended nutrient concentration produced the highest total yield. Treatment of plants with mycorrhiza did not significantly influence tomato yield.

The number and mass of fruit exhibiting cracking was significantly higher on plants

under NTC than under TC conditions (Table 3). Plants inoculated with mycorrhiza produced significantly more fruit exhibiting cracking than non-inoculated plants.

Discussion

Successful mycorrhiza colonization of tomato roots together with survival of mycorrhiza under TC and NTC conditions was observed, independent of the nutrient concentration supplied by the fertigation system. Inoculation with mycorrhiza resulted in higher

Mn and Zn concentration of tomato fruit under TC conditions, possibly due to the cooler environment (Table 8) favoring mycorrhizal development thereby enhancing nutrient uptake (Table 5). This is in agreement with Dasgan et al. (2008) who found that tomato plants inoculated with mycorrhiza and grown under soilless condition produce fruit with a higher Zn concentration than non-inoculated ones. Similarly, Cimen et al. (2010) reported an increase in tomato leaf mineral concentrations (P, K, Mg, Fe, Mn, Zn, and Cu), following AMF inoculation when tomato were grown in soil. However, in this study, mycorrhiza did not improve leaf mineral concentration significantly, possibly because plants were grown hydroponically, providing excess nutrients to the plant allowing sufficient nutrient uptake, even when the nutrient supply was reduced to 50% of the recommended nutrient concentration (Table 4). Liu et al. (2004) reported that temperature strongly influences mycorrhizal development; although root zone temperature was not measured in this experiment, the higher ambient air temperature in the NTC tunnel (44.2 °C) compared with the TC tunnel (34.5 °C) suggests that a relatively high root temperature was prevalent, negatively affecting root colonization as mycorrhizal development is optimal at root zone temperatures of between 20 and 25 °C (Zhang et al., 1997; Matsubara et al., 2000), with maximal spore germination occurring between 20 and 28 °C (Wang et al., 1997); nonetheless, the percentage mycorrhizal colonization observed under TC and NTC conditions exceeded colonization rates of tomato plants reported for TC greenhouses by Dasgan et al. (2008) and Cwala et al. (2010) and should have allowed better general nutrient uptake following colonization.

As high nutrient concentration reduces mycorrhizal colonization, the possible abundance of nutrients, especially of P (Ryan and Graham, 2002; Dasgan et al., 2008; Cwala et al., 2010), might have resulted in the inability of mycorrhiza to colonize roots completely (Dasgan et al., 2008); however, mycorrhiza colonization was not significantly affected by the supplied nutrient concentration in our study (Fig. 2).

Fig. 7. Interaction effects of production system and DAT on leaf length. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; LSD, least significant difference.

Fig. 8. Interaction effects of production system and DAT on leaf width. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; LSD, least significant difference.

Table 4. Effect of treatment on nutrient content of tomato fruits (dry mass) harvested from the fifth truss.

Treatment	% Moisture	P (mg·kg ⁻¹)	K (%)	Ca (mg·kg ⁻¹)	Mg (mg·kg ⁻¹)	Cu (mg·kg ⁻¹)	B (mg·kg ⁻¹)	Mn (mg·kg ⁻¹)	Fe (mg·kg ⁻¹)	Zn (mg·kg ⁻¹)
<i>Production system</i>										
NTC	93.97 b	4764.88 b	2.91 b	1529.83 b	1759.29 b	11.1 b	49.7	15.84 b	52.48 b	43.94 b
TC	95.25 a	6040.04 a	3.99 a	2552.58 a	2305.00 a	21.5 a	51.8	22.06 a	80.23 a	52.56 a
LSD _{0.05}	0.4	502.5	0.43	292.06	202.5	4.45	NS	2.18	13.40	5.72
<i>Nutrient concentration/Fertigation</i>										
F1	94.59	5287.72 a	3.06	1675.39	1787.37	17.2	45.7	18.67 a	58.95	49.13 a
F2	94.52	5318.24 a	3.06	1804.98	1835.87	16.6	55.0	16.01 b	63.47	44.67 ab
F3	94.29	4142.71 b	2.94	1590.24	1822.23	15.1	51.6	15.18 b	53.25	42.47 b
LSD _{0.05}	NS	398.13	NS	NS	NS	NS	NS	1.77	NS	5.28
<i>Mycorrhiza inoculation</i>										
+AMF	94.47	4737.98 b	2.97	1700.36	1775.62	16.0	49.0	15.70 b	60.95	45.34
-AMF	94.46	5094.46 a	3.07	1680.04	1854.69	16.6	52.6	17.54 a	56.16	45.51
LSD _{0.05}	NS	325.07	NS	NS	NS	NS	NS	1.44	NS	NS

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100; F2, 75; F3, 50% nutrient concentration; +AMF, plants inoculated with mycorrhiza; -AMF, plants without mycorrhiza; NS, not significant; LSD, least significant difference.

Fig. 9. Interaction effects of mycorrhiza inoculation and nutrient concentration on P concentration of tomato fruit. F1, 100%; F2, 75%; and F3, 50% of the recommended nutrient concentration; AMF (-), plant without mycorrhiza inoculation; AMF (+), plants inoculated with mycorrhiza. Values marked with the same letter are not significantly different ($P > 0.05$).

Fig. 10. Interaction effects of fertigation and production system on Mn concentration of tomato fruit. NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100%; F2, 75%; and F3, 50% of the recommended nutrient concentration; LSD, least significant difference. Values marked with the same letter are not significantly different ($P > 0.05$).

Table 5. Effect of production system and mycorrhiza inoculation on Mn and Zn concentration of tomato fruit.

Mycorrhiza inoculation	Production system			
	NTC	TC	NTC	TC
	Zn (mg.kg ⁻¹ DM)		Mn (mg.kg ⁻¹ DM)	
+AMF	42.85 c	57.33 a	14.60 d	23.3 a
-AMF	45.03 bc	47.78 b	17.07 c	20.77 b
LSD 0.05	4.74		1.54	

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

+AMF, plants inoculated with mycorrhiza; -AMF, plants without mycorrhiza; NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; LSD, least significant difference.

Despite a successful colonization rate of 35% to 60% (Fig. 2), mycorrhiza did not improve vegetative growth of tomato plants (Table 2), a finding in contrast to observations by Ikiz et al. (2009) that mycorrhiza increases plant growth of pepper under soilless conditions. Despite the higher root colonization in our experiment compared with reports by Dasgan et al. (2008), there was no significant improvement in tomato yield. Similarly, there was no improvement in tomato plant growth, and perhaps other media could have been more suitable in establishing the mycorrhiza-root interface, as Tajudeen et al. (2010) reported that the effectiveness of mycorrhiza inoculum is related to the choice of the growing medium.

Generally, plants fertigated with 75% (F2) of the recommended fertilizer rate dis-

played more vigorous growth, a larger leaf area, and a thicker stem diameter than those supplied with the full (F1) and the lowest (F3) nutrient concentrations. The significantly higher total yield of plants fertigated with F2 than F1 and F3 (Table 3) might be related to the more vigorous plant growth (thicker stem diameter, larger leaves; Fig. 3 and Table 2). Results indicate that high yields can be obtained when applying only 75% of the recommended nutrient concentration; therefore, further studies need to investigate optimal fertilization regimes for tomato cultivars as the present general recommendations seem to exceed nutrient needs of the tested tomato cultivar.

High air temperatures adversely affect vegetative and generative growth of tomato

plants; optimal temperatures for tomato production lie between 18 and 28 °C (Saeed et al., 2007). The higher temperatures under NTC (37.7 to 44.2 °C) compared with TC conditions (24.1–34.5) stimulated plants to grow taller (Fig. 5), while stem diameter and leaf area decreased under such conditions (Figs. 4, 7, and 8), which could be a heat stress effect. Plants grown under NTC conditions tended to produce more leaves than plants grown under TC (Table 2); however, plants grown under TC conditions developed vigorously, displaying initially larger leaves (length and width) and a wider stem diameter, which, 56 DAT, tended to decrease, probably due to competition from reproductive sinks (Figs. 4, 7, and 8) (Hanssens et al., 2011). At this developmental stage, more assimilates might have been channeled to fruit and flower instead of vegetative development, as fruit growth accounts for 80% to 90% of the fresh plant weight gain in tomato (Ho, 1988), and fruit are stronger sinks for assimilates than leaves (Ho, 1984). Because of high temperatures under NTC conditions stomatal closure is likely to have occurred (Marcelis and Heuvelink, 2007) leading to reduced transpiration and photosynthesis, while respiratory processes were enhanced, as Morales et al. (2003) reported that high temperatures (33 to 40 °C) decrease chlorophyll content, photosynthetic rate, and stomatal conductance of tomato plants. Consequently, biomass production and xylem transport rates decrease due to smaller leaf area and reduced stem thickness, resulting in reduced yield and fruit quality.

A significantly lower total and marketable yield under NTC conditions, compared with TC conditions, was associated with lower fruit set and accelerated fruit ripening while fruit were still small, resulting in an average fruit size of only 98.4 g under NTC, compared with 132.8 g under TC conditions (Table 3). The air temperature under TC conditions (24.1 to 34.5 °C) was better suited for tomato growth and development than the temperatures prevailing under NTC conditions (37.7 to 44.5 °C). Jones (2008) reported the optimal air temperature range for tomato fruit set to lie between 18.5 and 26.5 °C, with day and night time temperatures ranging between 21 to 29.5 °C and 18.5 to 21 °C, respectively. The temperature differences (Table 8) between TC and NTC conditions are likely to have contributed to reduced fruit set under the latter conditions. The viability of tomato pollen is severely reduced by temperatures above 29 °C resulting in reduced fruit set (Abdul-Baki and Stommel, 1995; Peet and Bartholomew, 1996; Sato et al., 2000). Relying on natural ventilation to counteract heat buildup in tunnels seems insufficient to reduce ambient temperatures to below 37.7 °C (Maboko et al., 2012), particularly in summer (Table 3), thereby reducing tomato yield (Table 3); therefore, cheaper cooling systems or cultivars that tolerate higher temperatures need to be developed to improve fruit set, yield, and quality of tomato under NTC conditions. Total and

Table 6. Effects of treatment on nutrient concentration of tomato leaves (fourth leaf from growing point) 90 d after transplanting.

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Cu (mg·kg ⁻¹)	B (mg·kg ⁻¹)	Mn (mg·kg ⁻¹)	Fe (mg·kg ⁻¹)	Zn (mg·kg ⁻¹)
<i>Production system</i>										
NTC	3.15 b	0.38 b	2.39 b	3.30 b	0.92 a	38.8	82.9 a	116.9	86.8 a	53.7 a
TC	3.94 a	0.59 a	3.10 a	3.81 a	0.75 b	41.1	57.9 b	108.8	69.7 b	40.5 b
LSD _{0.05}	0.17	0.057	0.30	0.36	0.102	NS	6.62	NS	10.39	7.85
<i>Nutrient concentration/Fertigation</i>										
F1	3.90 a	0.67 a	3.25 a	3.40	0.77 b	39.8	72.9	133.7	85.9	50.8
F2	3.49 b	0.48 b	2.78 b	3.41	0.88 a	42.4	71.6	106.6	74.6	45.6
F3	3.24 c	0.32 c	2.19 c	3.36	0.98 a	37.6	66.8	98.3	74.3	44.9
LSD _{0.05}	0.21	0.07	0.37	NS	0.107	NS	NS	NS	NS	NS

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100; F2, 75; F3, 50% nutrient concentration; NS, not significant; LSD, least significant difference.

marketable yield can be improved under TC conditions (Table 3), confirming results by Peet et al. (1997) and Mutwiwa et al. (2007) that pad and fan cooling systems can improve tomato fruit set.

Wet walls were effective in reducing the ambient temperature under TC conditions, subsequently cooling fruit. Temperature fluctuations in medium- (50–60 mm) to small-sized (40–50 mm) tomato fruit under NTC

conditions might have exacerbated the incidence of fruit cracking in such fruit, as high temperatures and the lack of exocarp elasticity when fruit expand can result in rupturing of the epidermis (Peet, 1992; Cheryld et al., 1997). An imbalance in fruit water supply and fruit water loss, which is likely to have occurred as a result of temperature fluctuations under NTC conditions, has been reported to cause fruit cracking (Dorais et al., 2001). The higher moisture content of tomatoes produced under TC compared with NTC conditions (Table 4) indicates that such fruit were able to maintain higher moisture levels. The improved nutritional fruit quality under TC conditions indicates a potential marketing tool for such tomatoes as fruit of higher quality than those under NTC conditions. The lower resistance to physiological disorder (fruit cracking) of NTC than TC tomatoes (Maboko et al., 2012) is also reflected in the lower concentrations of macroelements (N, P, K, and Ca) in leaves from NTC plants, probably due to poor water movement in the plant.

Many fruit-related disorders are aligned to Ca deficiency. As Ca is an integral part of the cell membrane, a low fruit Ca concentration reduces membrane integrity (Saure,

2001). The Ca concentration in fruit produced under TC conditions was higher than that under NTC conditions (Table 4). Low humidity caused by high temperatures can increase transpiration, and a relatively greater proportion of Ca moves into leaves than into, particularly fully expanded, fruit (Adams and Ho, 1993). Calcium was found to be present in low concentrations in tomato fruit and leaves under NTC conditions, which might have exacerbated fruit cracking (Maboko et al., 2013). Although plants cultivated under NTC conditions experienced high ambient air temperatures, it was expected that mycorrhiza would benefit plants, resulting in adequate water supply with reduced fertilizer application. Mycorrhiza, however, did not improve plant or fruit growth, yield, and fruit mineral concentration under reduced nutrient supply, but may have reduced the negative effect of low Ca supply, which was recorded in tomatoes produced under NTC conditions.

Conclusions

Results illustrate that reducing summer heat in tunnel production can improve yield and quality of tunnel tomatoes while emphasizing the possibility to reduce the recommended amount of fertilizer applied. Fertigating plants with 75% of the recommended nutrient strength improved yield and quality of tomatoes, compared with the recommended (100%) and half the recommended quantity. Growing plants under TC conditions increases vegetative growth (stem diameter and leaf size) as well as tomato fruit nutrient (N, P, K, Ca, Mn, Fe, Zn, Cu, and Mg) concentrations. Mycorrhiza inoculation of plants maintained in open-bag hydroponic systems using sawdust as a growing medium does not significantly influence vegetative growth or yield, but little effect of mycorrhiza inoculation on fruit macronutrient concentrations was observed; however, Zn and Mn concentrations of tomato fruit in the TC tunnel was enhanced by such inoculation. Further studies need to be undertaken to determine why the successful mycorrhizal colonization did not enhance yield or nutrient use but improved fruit nutrient concentration of tomatoes maintained under soilless conditions.

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Table 7. Interaction effects of production system and fertigation on Fe and Zn content of tomato leaves.

Fertigation	Production system			
	NTC	TC	NTC	TC
	Fe (mg·kg ⁻¹ DM)		Zn (mg·kg ⁻¹ DM)	
F1	84.88 a	87.01 a	52.79 ab	48.90 ab
F2	90.04 a	59.1 b	48.42 ab	42.70 bc
F3	85.60 a	62.96 b	59.80 a	29.95 c
LSD _{0.05}	17.99		13.59	

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100; F2, 75; F3, 50% nutrient concentration; LSD, least significant difference.

Table 8. Maximum, minimum, and mean monthly ambient temperatures of the tunnels during the experimental period.

Production system	Stem diam (mm)	Plant ht (mm)	Number of leaves/plant	Leaf length (mm)	Leaf width (mm)
NTC	12.74	1515.8 a	17.30	321.3 b	254.0 b
TC	14.11	1443.8 b	16.79	357.7 a	297.1 a
LSD _{0.05}	NS	51.20	NS	4.99	15.09
<i>Nutrient concentration/fertigation</i>					
F1	13.28 b	1490.6	17.09	344.8 a	280.8 a
F2	14.00 a	1479.2	17.18	345.8 a	283.1 a
F3	12.99 b	1469.7	16.87	328.0 b	262.8 b
LSD _{0.05}	0.586	NS	NS	10.05	10.38
<i>Mycorrhiza inoculation</i>					
+AMF	13.36	1490.0	17.3	339.5	274.8
-AMF	13.48	1469.6	16.8	339.6	276.3
LSD _{0.05}	NS	NS	NS	NS	NS
<i>Number of DAT</i>					
28	12.34 c	743.0 a	12.12 c	277.1 c	218.3 c
42	13.57 b	1128.6 b	12.84 c	338.1 b	283.7 b
56	12.72 c	1588.3 c	17.56 b	337.4 b	285.0 b
70	14.04 ab	1940.7 d	21.02 a	370.4 a	299.5 a
84	14.45 a	1998.5 e	21.68 a	374.7 a	291.3 ab
LSD _{0.05}	0.706	51.20	0.902	6.54	9.49

Values in a column followed by the same letter are not significantly different ($P > 0.05$), using Fishers' protected t test.

NTC, non-temperature-controlled tunnel; TC, temperature-controlled tunnel; F1, 100; F2, 75; F3, 50% nutrient concentration; +AMF, plants inoculated with mycorrhiza; -AMF, plants without mycorrhiza; NS, not significant; LSD, least significant difference.

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