

Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: a review

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Abstract. Greenhouse technology is a flexible solution for sustainable year-round cultivation of Tomato (*Lycopersicon esculentum* Mill), particularly in regions with adverse climate conditions or limited land and resources. Accurate knowledge about plant requirements at different growth stages, and under various light conditions, can contribute to the design of adaptive control strategies for a more cost-effective and competitive production. In this context, different scientific publications have recommended different values of microclimate parameters at different tomato growth stages. This paper provides a detailed summary of optimal, marginal and failure air and root-zone temperatures, relative humidity and vapour pressure deficit for successful greenhouse cultivation of tomato. Graphical representations of the membership function model to define the optimality degrees of these three parameters are included with a view to determining how close the greenhouse microclimate is to the optimal condition. Several production constraints have also been discussed to highlight the short and long-term effects of adverse microclimate conditions on the quality and yield of tomato, which are associated with interactions between suboptimal parameters, greenhouse environment and growth responses.

Keywords: optimal air temperature, relative humidity, vapour pressure deficit, greenhouse, tomato, membership functions

INTRODUCTION

Sustainable greenhouse production requires the integration of information and management strategies, as well as excellent understanding of the influencing microclimate parameters. In this regard, the proper understanding of the

variations in greenhouse microclimate, in conjunction with the requirements of tomato at different growth stages, merit special attention. Tomato (*Lycopersicon esculentum*) is one of the most widely-grown greenhouse vegetables in the world (Viuda-Martos *et al.*, 2014), and it is highly demanded by fresh market and processing industries. It favours moderate to warm climate with additional light improving fruit development and yield. Moreover, tomato can grow well in soil, organic substrates, soilless mixes, perlite, sand or hydroponic. Different techniques and methods of determinant and indeterminate varieties of tomato planting under open-field and greenhouse conditions are available in the textbooks of Cherie (2010), Hochmuth and Hochmuth (2012), Jones (2013), and Van Ploeg and Heuvelink (2005). A comprehensive review of tomato by-products with respect to human health benefits and applications is available in the work of Viuda-Martos *et al.* (2014).

A greenhouse is defined as a covered structure that can provide plants with optimally-controlled microclimate growth conditions. In cold climates, there is a great advantage in having a controlled environment, whereas for moderate and tropical regions, it provides an extension of the production season and protection against diseases and insects. The greenhouse environment encompasses climatic and nutritional elements, along with structural and mechanical conditions. If properly managed, it can significantly

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increase fruit quality and yields. Since the costs associated with greenhouse cultivation are generally higher, due to the initial investments in the structure, equipment and energy, the understanding of optimal microclimate parameters for automatic control is necessary to achieve high yield at low expenses and to keep the production efficient. The success of system analyses in greenhouse automation and control relies on the effective use of information. Reducing the excessive energy required for greenhouse heating and cooling, especially in regions with adverse climate conditions, is a major concern in terms of maintaining a competitive power in the market. For instance, fruit yield and quality of tomato are directly affected by microclimate parameters. As tomato plants are sensitive to both high and low air temperatures, greenhouse cultivation in the regions displaying such climate conditions that are not adequately close to the base requirements will involve additional risks and production costs. Therefore, an important sustainability challenge lies in shifting from energy-consuming, to energy-neutral greenhouses. This can be done by accurately assessing short and long-term risks associated with the interactions between climate conditions, greenhouse environment and growth responses. In other words, knowing how far from optimal a greenhouse microclimate can be, without sacrificing production quality and yield, would contribute to the creation of a proper automation level for energy management and environmental impact reduction, as well as to the maximisation of the use of natural resources (*i.e.*, to successfully shifting from greenhouses with advanced climate control systems, to those that maximise efficient use of shading and natural ventilation).

The main environmental factors affecting greenhouse tomato include air and root-zone temperatures, relative humidity (*RH*), light conditions (*L*), disease and insect intervention, as well as carbon dioxide (Jones, 2013). The adequate management of these parameters, in order to achieve maximum returns with minimum energy inputs, has a direct impact on tomato growth development and plays a crucial role in preventing crop stress. This paper reviews the optimal and marginal temperature levels, *RH* values and vapour pressure deficit (*VPD*) for the greenhouse cultivation of tomato at different growth stages and under different light conditions. These parameters are known for influencing plant evapotranspiration and have significant effects on growth and physiological cycles. A sufficiently detailed summary of literature addressing adverse microclimate effects on tomato fruit quality and yield, as well as cultivation constraints with suboptimal values, is provided. Such information will contribute to knowledge-based decision-support systems for efficient energy management in greenhouse climate control and cost-effective year-round cultivation. It can also be used in the design of more flexible micro-climate control strategies through better understanding of the control parameters and their interactions with tomato productivity and yield. Plant

responses to other influencing factors such as carbon dioxide, nutrient solution, cultivar variety and grower skill are covered in the textbook of Morison and Morecroft (2006).

GROWTH STAGES OF TOMATO

The optimum levels of microclimate for the best greenhouse cultivation of tomato depend on different growth stages and light conditions. The five growth stages of tomato are described by Jones (2013) and García *et al.* (2011) as germination and early growth with initial leaves (between 25 and 35 days), vegetative period (20 to 25 days), flowering (20 to 30 days), early fruiting (20 to 30 days), and mature fruiting (15 to 20 days). The exact days within each stage depend on the varieties and other environmental factors such as air temperature, light condition, soil conditions and nutrients. Moreover, some varieties have been hybridized to specific climate or might be more sun tolerant, which makes their fruit production time shorter. The average duration to reach the mature fruiting stage (from transplanting) for most greenhouse tomato varieties, depending on the cultivar, different maturity levels and ripeness, is between 65 to 100 days. The estimated time from planting to marketable maturity is between 50 and 65 days for an early variety, and between 85 and 95 days for a late variety (Jones, 2013). Another source (García *et al.*, 2011) reported two growth periods of 133 days and 126 days in two different experiments. However, a minimum of 75 days from transplanting was reported to be required to reach the first harvest for most cultivated tomatoes (Jones, 2013). Medium early varieties like 'Champion' and 'Mountain Spring' have average production of about 65 days. Main Crop varieties, including 'Brandywine', 'Celebrity', 'Better Boy', 'Fantastic', 'Burpee's Big Girl', 'Sioux', 'Mountain Pride' and 'Supersonic' are considered to be the tastiest and of best quality within 70 and 80 days. Furthermore, extra-large tomato varieties such as 'Beefsteak', 'Shuntuksi Velikan' and 'Neves Azorean Red' have an average production time of about 80 to 85 days. Thus, the number of days from seeding to harvesting of the first fruits, according to Jones (2013), varies from 45 days to over 100 days, depending on the maturity level of the cultivar. The five growth stages of tomato are illustrated graphically in Fig. 1, along with different fruit maturity levels and ripeness. It should be noted that tomatoes are harvested two to four times a week, and only when they have reached the mature green stage (vine-ripe), as they start to ripen.

OPTIMUM AIR AND ROOT-ZONE TEMPERATURE

Maintaining an optimum average daily air temperature is crucial for pollen development and also for maintaining a good anther in tomato flowers. Different references have reported different values of air temperature and humidity to be optimal for each specific growth stage. For example, Sato *et al.* (2000) recommended as optimal, air temperature

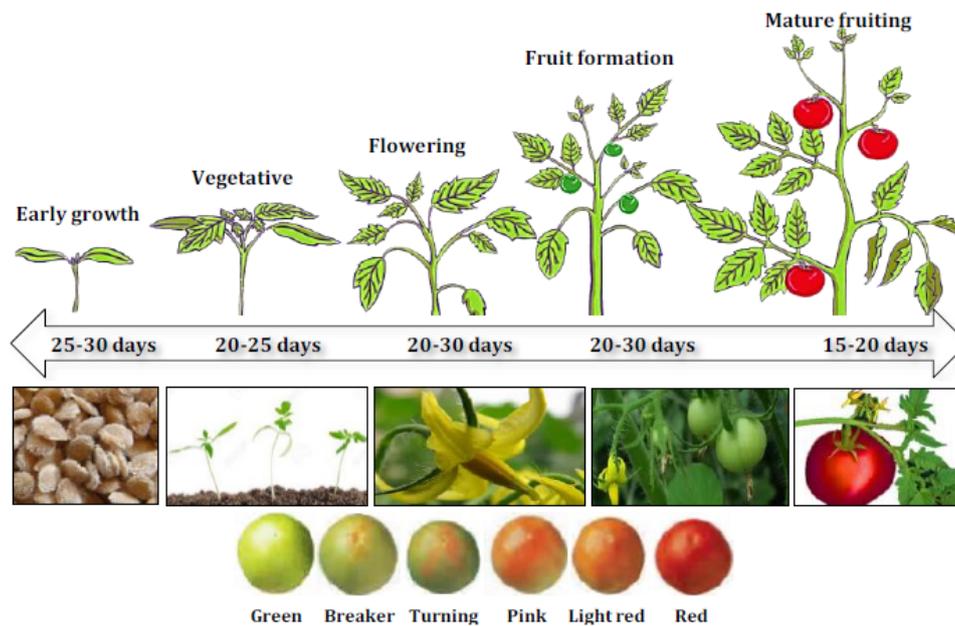


Fig. 1. Demonstration of the five growth stages of tomato, and the different levels of fruit ripeness.

of 22°C for leaf/truss development, 22-26°C for fruit addition and 22-25°C for fruit growth and fruit-set. Greenhouse crops are mostly warm-season crops which are adapted to optimal air temperatures between 17-27°C, with the lower and upper marginal temperature of 10 and 35°C (Kittas *et al.*, 2005). In general, values between 18.3 and 32.2°C are considered to be optimal air temperatures for tomato during the entire growing season (Cherie, 2010; Hochmuth and Hochmuth, 2012). Fundamental requirements regarding the cultivation environment of tomato are considered by Baudoin *et al.* (2013) as an average ambient air temperature in the range of 17-28°C in coastal areas and 17-22°C in inland areas far from the sea (with the minimum and maximum tolerable values of 12 and 32°C, and the minimum global radiation of 2.34 kWh m⁻² day⁻¹). This difference is due to the fact that the daily temperature fluctuations in inland areas are around 20°C, and approximately 10°C higher than those in coastal areas (Baudoin *et al.*, 2013). For proper physiological functioning, tomato requires thermal periodicity (an average temperature difference between day and night) between 5 and 7°C, with at least 500-550 h of day light in the usual three-month growing season (an average of 6 h light day⁻¹) (Baudoin *et al.*, 2013). Under hot and humid tropical climate conditions, Ajwang and Tantau (2005) reported that while air temperature can rise to 38°C, the temperature inside a greenhouse without a climate controller may be 20-30°C higher than outside (Kittas *et al.*, 2005). The same source considered temperatures above 26°C as failure values and suggested that values exceeding 25°C would most likely reduce tomato production. Kittas *et al.* (2005) also suggested that the maximum greenhouse air temperature should not exceed 30-35°C. Under the hot climate conditions of Mediterranean summer months, Harel

et al. (2014) thought that an average daily temperature of up to 26°C could be achieved in a greenhouse shelter when using evaporative cooling such as low pressure fogging systems. The optimal air temperature for tomato germination is recommended to be at 25°C, by Van Ploeg and Heuvelink (2005), followed by the minimum night time temperature of 18°C and the daily maximum of 27°C for seedling growth. Jones (2013) recommended that the ideal air temperature for seedling growth should be between 16 and 18.5°C. Moreover, Adams *et al.* (2001) claimed that the rate of fruit addition (fruit-set, from pollination) had an optimum air temperature at or lower than 26°C and progressively failed with temperature reaching 32°C. Finally, air temperatures of 18.5-26.5°C with day and night temperatures, respectively, between 21-29.5°C and 18.5-21°C were reported to be optimal (Jones 2013).

Studies have shown that canopy (leaf) temperature may be far more important in plant growth. The combination of RH and the plant transpiration rate determine the canopy temperature. The optimal range for air temperature inside the canopy is recommended to be between 20 and 22°C (Jones, 2013). Results of simulation with an adaptive management framework (Shamshiri *et al.*, 2017a) and the TOMGRO model (Jones *et al.*, 1999) are consistent with these findings, showing that for hot and humid tropical climates, the lower and upper marginal borders of air temperature for germination is 16 and 30°C, for maximum yield 20 and 25°C, and for growth development 12 and 30°C. It is suggested that the lowest tolerable and optimum air temperature should be, respectively, kept at 7 and 22°C for the rate of leaf appearance, the rate of truss appearance and the rate of progress (Adams *et al.*, 2001). In addition, the rate of fruit development and maturation has a base

temperature of 5.7°C and an optimum temperature of 26°C, while the rate of individual fruit growth has its optimum at 22-25°C (Adams *et al.*, 2001). Finally, according to Duchowski and Brazaitytė (2001), leaf photosynthesis of tomato has a base air temperature of 6-8°C, with the optimum established at 30°C.

Root-zone temperature also affects tomato growth, especially in the processes of shoot formation and flowering. However, interaction may exist with air temperature, solar radiation and length of day light. Jones (2013) put forward that a root-zone temperature of 27°C would be ideal for tomato, while, Li *et al.* (2015) observed that a root-zone temperature of 23°C during summer had the least drought stress effect on tomato between treatments in the range of 22 and 33°C. Furthermore, Ntatsi *et al.* (2014) reported that, as compared to an optimal root-zone temperature of 25°C, leaf area expansion of tomato, as well as shoot elongation and plant biomass were decreased at a suboptimal root-zone temperature of 15°C. Reports indicate that in cold regions, under optimal greenhouse air temperature, root-zone heating first improves the root growth, and then influences the shoot growth (Kawasaki *et al.*, 2014; Shishido and Kumakura, 1994; Tindall *et al.*, 1990). A comprehensive review of the effects of root-zone temperature on plant growth is available in the works of Vogelegang (1993) and Li *et al.* (2015). Tomato yield was also found to be significantly positively correlated with soil moisture content (Chen *et al.*, 2015). The optimum soil temperature for tomato germination, at which seedlings are likely to emerge between 5 and 7 days, is 29.5°C (Olson *et al.*, 2012). The minimum required temperature for seed germination is 8-10°C, with the optimum range between 16-29.5°C, and the maximum tolerable temperature of 35°C (Jones, 2013). The time to germination declines from 14 to 5 days with a temperature increase from 15.5 to 29.5°C, and it then grows to 9 at 35°C (Olson *et al.*, 2012). In addition, the number of days to seedling emergence decrease from 43 to 6 with an increase in soil temperature from 10 to 30°C, and it then grows to 9 at temperatures above 35°C (Jones, 2013). Furthermore, the ideal soil temperature, depending on the light intensity and the phase of growth and development, is reported in the range of 13 to 25°C by Mahajan and Singh (2006). Baudoin *et al.* (2013) held that during night and cloud hours, the optimal soil temperature for the development stage, flowering stage and harvesting stage was, respectively, between 13-14, 15-16, and 20-22°C, while these values during sun hours were 17-20, 19-22, and 23-25°C, respectively. They, therefore, recommended that soil temperature should be larger than 14°C, when ambient *RH* is between 70 and 90%. Depending on the stage of development, a summary of reviewed literature that suggested optimal, marginal, and failure temperature for greenhouse cultivation of tomato is provided Table 1.

OPTIMUM HUMIDITY AND VAPOUR PRESSURE DEFICIT

Total greenhouse humidity is the result of condensation on the covering, vapour losses from ventilation and the balance between plants transpiration and soil evapotranspiration. It is expressed in scientific literature as absolute humidity (g m^{-3}), specific humidity (g water kg^{-1} air) or relative humidity (percentage); the latter, however, being more common. For most greenhouse tomato varieties, relative humidity range between 60-90% is considered appropriate by ASABE (2015) standards. Moreover, the optimal range of relative humidity during the entire growth stages of tomato is suggested to be between 50-70%. Studies also show that Tomato pollination is significantly enhanced when *RH* is around 60% (Harel *et al.*, 2014). It should be underlined that plants exposed to higher temperature require higher humidity (Kittas *et al.*, 2005). This is related to the plant transpiration. Thus, in a greenhouse condition with air around plant leaves too hot and humid, the transpiration at the leaf surface will be ineffectual and the root and stem system may not be able to supply adequate water to the leaves. Cooling is, therefore, required to reduce these stresses. In regions with cold climate, *RH* is generally low due to lower transpiration and higher levels of condensation.

Humidity alone does not provide any information about plant transpiration, and it cannot be used as a good indicator of the vapour pressure stress on plants. The main parameter for controlling plant water uptake in the greenhouse environment, which, in turn, affects other physiological process (*i.e.*, pollination, growth and yield), is the air water vapour pressure deficit. It is the driving force for water movement between roots and leaves. *VPD* is the difference between saturation vapour pressure (e_s) and the actual vapour pressure (e_a). It is directly related to transpiration and affects the quality and yield of tomato fruits. The saturation water vapour pressure increases exponentially with an increase in air temperature. Estimation of plant evapotranspiration (*ET*) or water loss to the atmosphere depends on *VPD*. This parameter can also be used as an indication to determine how close a closed-field environment is to saturation. According to Zolnier *et al.* (2000), *VPD* is capable of more accurately reflecting how the plant feels by taking into account both the measurements of temperature and *RH*. Another important application of *VPD* estimation is to evaluate the condensation potential of a greenhouse crop and to identify when it is likely to happen. Reports also indicate that plant radiation use efficiency is related to *VPD* (Stockle and Kiniry, 1990). Several *ET* models that rely on *VPD* have been presented in the work of Jensen *et al.* (1990), along with a detailed discussion of its computation methods. Given *T* (°C) and *RH* (%), *VPD* can be computed from the following equation in kPa. A comprehensive discussion on the comparison between other computations

Table 1. Summary of reviewed literature suggesting optimal, marginal, and failure temperature for greenhouse cultivation of tomato. T_A – air temperature, T_r – root-zone temperature, T_s – soil temperature, F – failure, M – marginal, Op – optimal

Zone	Range (°C)	Level	Description of growth stage	Reference
T _A	<5.7	F	during fruit development and maturation	(Adams <i>et al.</i> , 2001)
T _A	[6,8]	F	base temperature for leaf photosynthesis	(Duchowski and Brazaitytė, 2001)
T _A	<7	F	during leaf appearance, rate of truss appearance, and rate of progress	(Adams <i>et al.</i> , 2001)
T _A	=8.5	F	was used in TOMGRO model	(Jones <i>et al.</i> , 1999)
T _s	[8,10]	M	minimum required soil temperature for seed germination	(Jones, 2013)
T _A	<12 or >30	M	growth development (in warm climates)	(Jain, 2012)
T _s	[13,14]	Op	soil temperature, development before flowering, (night and cloud)	(Popovski, 1997)
T _s	=14	M	minimum recommended for most greenhouse crops	(Baudoin <i>et al.</i> , 2013)
T _r	<15	F	decreases leaf area expansion, shoot elongation and plant biomass	(Ntatsi <i>et al.</i> , 2014)
T _s	[15,16]	Op	soil temperature, flowering (night and cloud)	(Popovski, 1997)
T _s	[15.5,29.5]	Op	soil temperature for germination, the time to germination declines from 14 to 5 days with increasing of temperature from 15.5 to 29.5°C	(Olson <i>et al.</i> , 2012)
T _A	[16,18.5]	Op	for seedling growth	(Jones, 2013)
T _A	<16 or >30	M	for germination (in warm climates)	(Jain, 2012)
T _s	[16,29.5]	Op	soil temperature for seed germination	(Jones, 2013)
T _A	[17,19]	Op	for full harvest (night)	(Omafra, 2005)
T _s	[17,20]	Op	soil temperature, development before flowering, sun	(Popovski, 1997)
T _A	[17,22]	Op	inland areas far from the sea	(Baudoin <i>et al.</i> , 2013)
T _A	[17,27]	Op	for all growth stages	(Kittas <i>et al.</i> , 2005)
T _A	[17,28]	Op	in coastal areas	(Baudoin <i>et al.</i> , 2013)
T _A	<18 or >27	M	minimum night time and maximum day time for seedling growth	(Van Ploeg and Heuvelink 2005)
T _A	[18.3,32.2]	Op	for all growth stages	(Hochmuth and Hochmuth 2012; Cherie, 2010)
T _A	[18.5,21]	Op	for all growth stages during night time	(Jones, 2013)
T _A	[18.5,26.5]	Op	general recommendation for all growth stages and light conditions	(Jones, 2013)
T _A	=19	Op	for mature fruit, initiation of harvesting (day and night)	(Omafra, 2005)
T _A	[19,21]	Op	for plant raising (day and night)	(Omafra, 2005)
T _s	[19,22]	Op	soil temperature, flowering, sun	(Popovski, 1997)
T _A	[20,22]	Op	for canopy temperature (light condition NA), for full harvest (daylight)	(Jones, 2013; Omafra, 2005)
T _s	[20-22]	Op	soil temperature, harvesting, (night and cloud)	(Popovski, 1997)
T _A	<20 or >25	M	harvesting stage (in warm climates)	(Jain, 2012)
T _A	[21,29.5]	Op	for all growth stages during day time	(Jones, 2013)
T _A	=22	Op	for leaf and truss development, for rate of leaf appearance, rate of truss appearance, and rate of progress	(Sato <i>et al.</i> , 2000; Adamset <i>et al.</i> , 2001)
T _A	[22,25]	Op	for fruit growth and fruit-set, rate of individual fruit growth will be optimum	(Adams <i>et al.</i> , 2001; Sato <i>et al.</i> , 2000)
T _A	[22,26]	Op	for fruit addition	(Sato <i>et al.</i> , 2000)

Table 1. Continuation

Zone	Range (°C)	Level	Description of growth stage	Reference
T _r	=23	Op	during summer for least drought stress	(Li <i>et al.</i> , 2015)
T _s	[23,25]	Op	soil temperature, harvesting, sun	(Popovski, 1997)
T _A	=24	Op	for transplanting (day and night)	(Omafra, 2005)
T _A	=24.4	M	used in TOMGRO model as minimum as critical daytime temperature, fruit growth was reduced when daytime temperature average exceeded this value	(Jones <i>et al.</i> , 1999)
T _A	=25	Op	for germination (day and night)	(Van Ploeg and Heuvelink, 2005; Omafra, 2005)
T _r	=25	Op	for optimized leaf area expansion, shoot elongation and plant biomass	(Ntatsi <i>et al.</i> , 2014)
T _A	[25,26]	M	will likely reduce tomato production	(Kittas <i>et al.</i> , 2005)
T _A	=26	Op	for best rate of fruit addition (fruit-set, from pollination), fruit development and maturation	(Adams <i>et al.</i> , 2001)
T _A	=26	M	fruit growth was found to reduce sharply with increasing of mean daytime temperature above this value due to fruit abortion	(Jones <i>et al.</i> , 1991)
T _r	=27	Op	NO Information available	(Vermeulen <i>et al.</i> , 2012)
T _s	=29.5	Op	seedlings will emerge between 5 and 7 days	(Olson <i>et al.</i> , 2012)
T _A	=30	Op	for leaf photosynthesis	(Duchowski and Brazaitytė 2001)
T _s	=30	Op	number of days to seedling emergence decrease from 43 to 6 with increasing of T _s from 10 to 30°C	(Jones <i>et al.</i> , 1999)
T _A	>30	F	NA	(Kittas <i>et al.</i> , 2005)
T _A	≥32	F	fruit-set progressively fails after this temperature	(Adams <i>et al.</i> , 2001)
T _s	≥35	F	maximum tolerable soil temperature for seed germination, the time to germination increase from 5 days to 9 days	(Jones, 2013; Olson <i>et al.</i> , 2012)
T _s	≥35	M	number of days to seedling emergence increase from 6 to 9 days	(Jones, 2013)

methods, enhancement factors relating e_s to temperature, VPD application in greenhouse cultivation, and indications of high or low values can be found in the works of (Abteu and Melesse, 2013).

$$VPD = \exp(6.41 + 0.0727T - 3 \cdot 10^{-4}T^2 + 1.18 \cdot 10^{-6}T^3 - 3.86 \cdot 10^{-9}T^4) \cdot (1 - RH/100).$$

Optimal VPD values are recommended in the range of 0.3 to 1.0 kPa in different sources. For example, Barker (1990) reports that VPD values between 0.5 and 0.8 kPa are optimal for most greenhouse crops and will prevent yield reduction due to fruit shrinkage and fungal diseases. What is more, VPD values between 0.2 and 1.0 kPa are recommended for both pollination and prevention from fungal diseases (Picken 1984; Prenger and Ling 2007). Iraqi *et al.* (1995) suggested $VPDs$ of 0.8 kPa as the optimal during day and night hours, and reported that both the photosynthetic rate and yield of tomato fruits increased when

compared with VPD treatments of 0.5 kPa. Moreover, values between 0.2 and 1.0 kPa were found to have little or no effect on the physiology and growth development of tomato (Grange and Hand, 1987; Picken, 1984). In another study on the effects of humidity on 26 different crops (Schwarz *et al.*, 2014), VPD between 0.3 and 1.0 kPa were reported to have minor effect, while values above 1.0 kPa were found to significantly affect plant growth. It is generally recommended that VPD should be kept around 0.3-0.5 kPa during root cuttings in order to minimize dry outs of plants, especially in dense plant conditions. This will also create a greenhouse environment that is less subjected to fungal diseases. Gautier *et al.* (2001) observed that optimal VPD enhances tomato fruit quality (higher sugar contents and dry matter weight) under low fruit load, while, Barker (1990) reported that problems associated with calcium deficiency can be avoided by maintaining optimal VPD . Factsheet (2015) considered VPD values between

0.47 and 1.27 kPa to be most suitable, and Omafra (2005) suggested values between 0.4-0.79 kPa to be the ideal *VPD* for most greenhouse crops. Tomato photosynthesis and nutrient uptake were also found to be optimal in this range. A popular agronomy weblog, Just4Growers, considered values of 0.75 and 1.06 kPa as the ideal range, and 0.45 and 1.25 kPa as marginal borders. This source also recommends that *VPD* below 0.45 kPa is the set-point to activate a dehumidification system, and that values over 1.25 kPa should

trigger humidification devices such as fog systems. A commercial greenhouse company (Argus, 2009) determined *VPD* between 0.5-1.2 kPa to be optimal, and 0.4-1.37 kPa to constitute marginal borders. A summary of the lower and upper optimal and marginal *T*, *RH* and *VPD*, as recommended by the last four reference sources mentioned, is provided in Table 2 and is followed by a descriptive summary for different values of *VPD* in greenhouse cultivation of tomato that is presented in Table 3.

Table 2. Summary of lower and upper optimal and marginal *T*, *RH* and *VPD* as recommended by four references

Reference	Lower optimal			Upper optimal			Lower marginal			Upper marginal		
	<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)	<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)	<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)	<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)
(Factsheet, 2015)	15	60	0.47	30	85	1.27	–	–	–	–	–	–
(Omafra, 2005)	15	55	0.40	30	90	0.79	–	–	–	–	–	–
Just4Growers	15	40	0.75	34	85	1.06	15	35	0.45	34	85	1.25
(Argus, 2009)	15	35	0.50	35	90	1.20	17	35	0.40	34	90	1.37

Table 3. Optimal range of vapour pressure deficit for greenhouse cultivation as suggested by different references

Range (kPa)	Description	Reference
0.2-1.0	ideal for pollination and for prevention from fungal disease, this range was found to have little or no negative effect on the physiology and growth development of tomato	(Picken 1984; Prenger and Ling 2001; Grange and Hand 1987)
0.3-1.0	studying the effect of humidity on 26 different crops showed this range has minor negative effects	(Hoffman, 1979)
0.4-0.79	ideal for most greenhouses crops, tomato's photosynthesis and nutrient uptake are optimal at this range	(Omafra, 2005)
<0.4 or >1.37	considered marginal values	(Argus, 2009)
<0.45 or >1.25	considered marginal values	Just4Growers
0.47-1.27	optimal for greenhouse cultivation	(Factsheet, 2015)
0.5-0.8	optimal for most greenhouse crops and will prevent from yield reduction due to shrinkage of fruit size and fungal diseases.	(Barker, 1990)
0.5-1.2	considered optimal	(Argus, 2009)
0.75-1.06	considered optimal	Just4Growers
0.8	optimal during day and night hours, reporting that both photosynthetic rate and yield of tomato fruits increased compared with treatments with 0.5 kPa <i>VPD</i>	(Iraqi <i>et al.</i> , 1995)
<0.45	the set-point to active dehumidification system	Just4Growers
>1.0	significantly affect plant's growth	(Hoffman, 1979)
>1.25 kPa	will trigger humidification devices such as fog systems.	Just4Growers

MICROCLIMATE EVALUATION WITH DECISION
SUPPORT SYSTEM (DSS)

HYTODMOD, OptVPD, and TOMGRO models

An interactive decision-support system (DSS) developed by Short *et al.*, (2005), based on the HYTODMOD growth response model of El-Attal (1995), is available to describe the optimality degrees of air temperature and RH at five growth stages and under three light conditions (night, sun and cloud). A graphical representation of this model for defining the optimal air temperature and RH has been reproduced from the original source and is provided in Fig. 2. These functions have been tested and validated by four independent expert growers and result from experiments with tomato ‘Caruso’ cultivar, in an A-Shape greenhouse located at the Ohio Agriculture Research and Development Centre with a floor area of 7.3 m². In order to develop membership functions for defining the optimality degrees of VPD, Shamshiri *et al.* (2017b) integrated the growth response model of El-Attal (1995) and developed the OptVPD model, along with a series of membership functions (Fig. 3).

Figure 3 with VPD (kPa) as inputs, and a real number between 0 and 1 as an output that defines the optimality degree of greenhouse VPD at different light conditions and growth stages of tomato. The knowledge behind the plots of Figs 2 and 3, and the optimal and failure microclimate values (Table 4), are condensed from an extensive peer reviewed scientific published research on greenhouse cultivation of tomato and physiology, with the goal of

simultaneously achieving high yield and high-quality fruit. A more in-depth analysis and practical examples of this DSS are presented by Shamshiri *et al.* (2017a) via an adaptive management framework.

The reduced state variable TOMGRO model (Jones *et al.*, 1999) was developed with the objective of providing a practical application with only five state variables as the node number for the main stem, the leaf area index, total plant dry weight (W_T), total fruit dry weight (W_F), and total mature fruit dry weight (W_M). Jones *et al.* (1999) provided simulation results for three tomato varieties, including ‘DeRuiters’, ‘Beefsteak’ and ‘Bigboy’, respectively, for three experiment locations at Gainesville (Florida), Avignon (France) and Lake City (Florida). They concluded that it is possible to use the simplified TOMGRO model for different climate conditions and different tomato varieties with the same parameters derived from their experiment. This conclusion was verified for tropical climate conditions in the lowlands of Malaysia (Shamshiri *et al.*, 2016a) using boundary data. Some of the other studies that adapted or validated TOMGRO model to specific climate conditions and cultural practices include the works of Schrevens *et al.* (2005), Dimokas *et al.* (2009) and Gallardo *et al.* (2009). It should be noted that the simplified TOMGRO model only takes into account the effect of air temperature and light condition, while other variables such as CO₂ concentration have not been included in this version. In addition, Jones *et al.* (1999) did not take the work any farther than making the model calculations in an Excel spreadsheet, hence the model did not have a practical application and could not

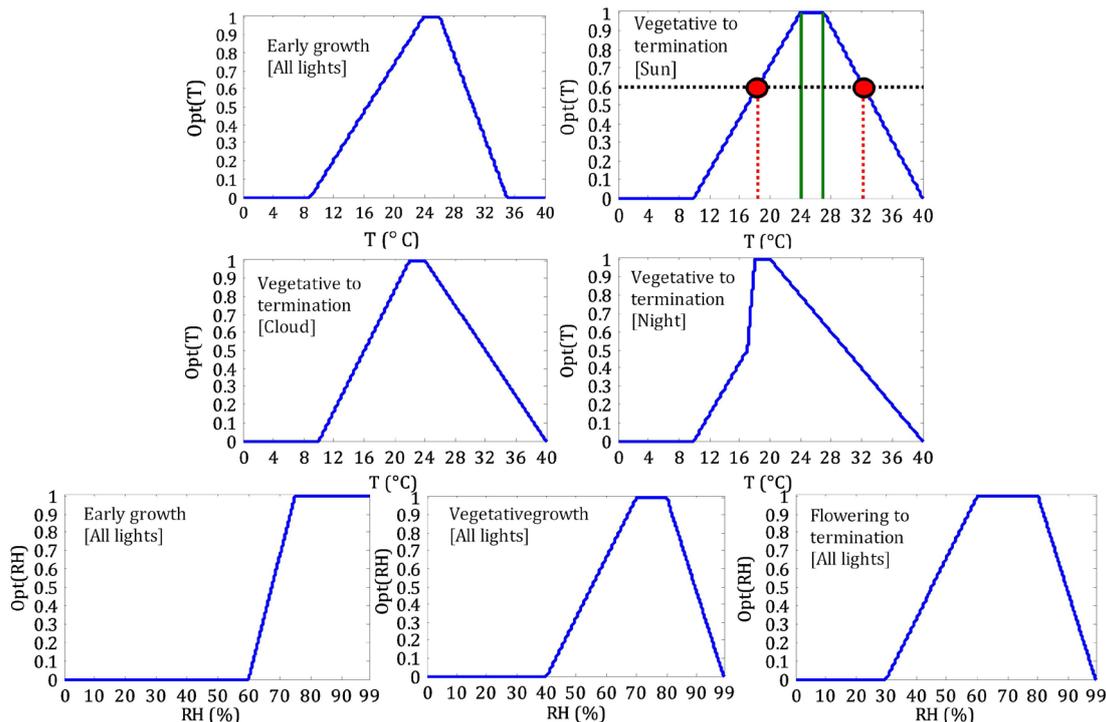


Fig. 2. Graphs of growth response function for defining optimal air temperature and relative humidity for the ‘Caruso’ greenhouse tomato cultivar at different growth stages and light conditions, adapted from (El-Attal, 1995).

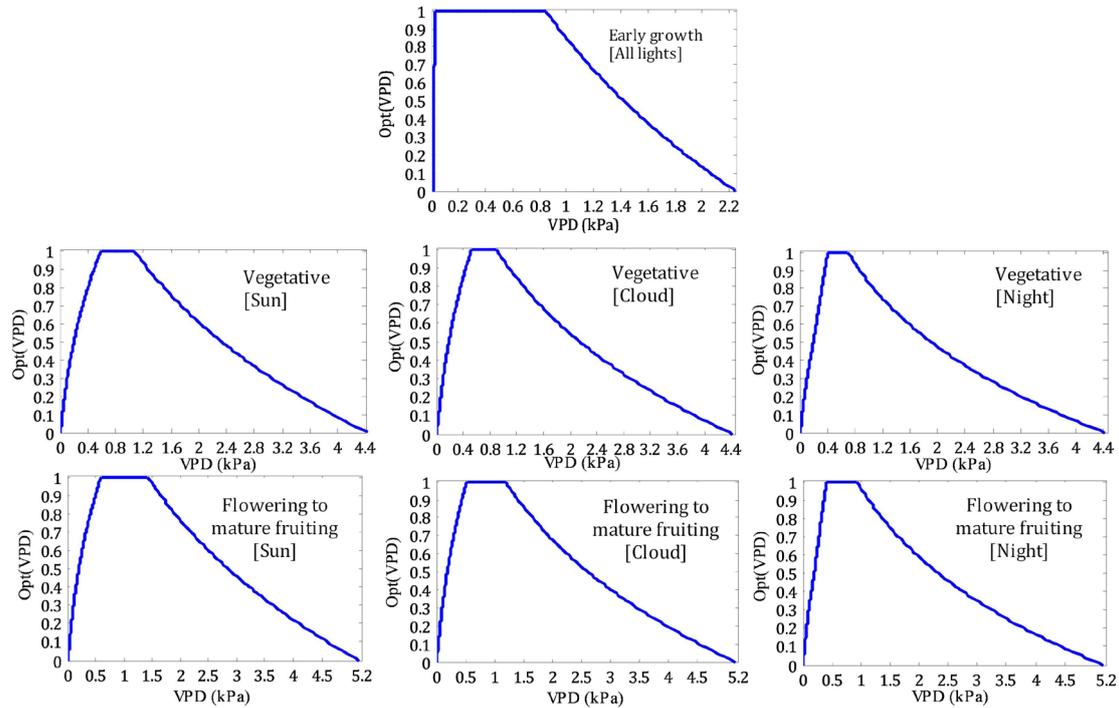


Fig. 3. Graphs of membership functions for defining optimality degrees of vapour pressure deficit at different light condition and growth stages for the ‘Caruso’ greenhouse tomato cultivar, adapted from (Shamshiri *et al.*, 2017b).

Table 4. Optimal and failure values of T , RH and VPD for the tomato cultivar ‘Carusso’, according to the decision support system of Short *et al.* (2005)

Growth stage	Light condition	Lower optimal			Upper optimal			Lower failure			Upper failure		
		T (°C)	RH (%)	VPD (kPa)	T (°C)	RH (%)	VPD (kPa)	T (°C)	RH (%)	VPD (kPa)	T (°C)	RH (%)	VPD (kPa)
Early growth	any	24	75	0.2	26.1	100	0.845	9	60	0.011	35	-	2.248
	sun	24	70	0.596	27	80	1.069	10	40	0.012	40	100	4.422
Vegetative	cloud	22	70	0.528	24	80	0.895	10	40	0.012	40	100	4.422
	night	18	70	0.413	20	80	0.701	10	40	0.012	40	100	4.422
Flowering to mature fruiting	sun	24	60	0.596	27	80	1.425	10	30	0.012	40	100	5.160
	cloud	22	60	0.528	24	80	1.193	10	30	0.012	40	100	5.160
	night	18	60	0.413	20	80	0.935	10	30	0.012	40	100	5.160

be used by greenhouse growers. To overcome this limitation, Shamshiri *et al.* (2017a) extended and implemented the TOMGRO model in SIMULINK and interfaced it with the HYTODMOD and OptVPD for microclimate evaluation and yield estimation.

Microclimate evaluation

The interfaced HYTODMOD, OptVPD, and TOMGRO model can be used as evaluation tools for exploring optimality degrees of microclimate, as well as for generating yield

estimation depending on the growth stage of the plant and different light condition. It also allows growers to manually change the values of the growing parameters and the growth stages and also to receive feedback by means of a number between 0 and 1 representing how close that parameter is to high yield and high quality. An application of this DSS has been presented for dynamic assessment (Shamshiri *et al.*, 2017c), for measuring optimality degrees (Shamshiri, 2017), and for establishing a comparative evaluation of microclimate parameters (Shamshiri *et al.*, 2016b) in greenhouses with different covering materials. Microclimate

evaluation with *VPD* influences the energy costs involved in greenhouse cultivation and must be taken into account in humidity and temperature control algorithms. It should be noted that *VPD* cannot be directly controlled since its value is not unique. Therefore, it should not be used directly as feedback of a closed-loop climate control system. For example, *VPD* = 0.85 kPa can result from different combinations of air temperature and *RH* (*i.e.*, $T=15^{\circ}\text{C}$ and $RH=50\%$, or $T=34^{\circ}\text{C}$ and $RH=84\%$). The relationship between air temperature, *RH* and *VPD*, when one parameter is kept constant, can be described using Table 5 and Fig 4. It can be seen that for a constant *RH*, the values of *VPD* increase at higher temperatures, resulting in an increase in the plant transpiration rate. The mathematical expression of *VPD* indicates that the maximum *VPD* value in a set belongs to a maximum temperature and minimum *RH* combination. Likewise, when air temperature is at the lowest value in the greenhouse and *RH* is at the highest level, *VPD* is

minimized. The figures displayed in Fig. 4 reveal that in order to maintain healthy *VPD* values at $RH = 70\text{-}75\%$, air temperature should be kept between 24 and 29°C. Table 5 also explains that at a constant *RH*, when air temperature increases from 20 to 30°C, *VPD* changes from 0.58 to 1.06 kPa. Moreover, at constant *VPD*, increasing air temperature from 14 to 34°C results in variation in *RH* from 47 to 84%. Of note, *VPD* can be effectively controlled by humidification devices such as fogging systems. Furthermore, as a general rule, increasing air temperature in the greenhouse by minimizing ventilation will increase *VPD*, while activating the evaporative cooling system, misting or fogging will cause higher *RH*, thus decreasing *VPD*. Psychrometric and ventilation constraints for *VPD* have been discussed in the work of Zolnier *et al.* (2000).

The results of studying fogging system *VPD* controllers on growth development and productivity of tomato in winter season (Lu *et al.*, 2015) showed that, on average,

Table 5. Variation in vapour pressure deficit due to different combination of temperature and relative humidity

Constant temperature			Constant relative humidity			Constant <i>VPD</i>		
<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)	<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)	<i>T</i> (°C)	<i>RH</i> (%)	<i>VPD</i> (kPa)
25	45	1.741	75	20	0.584	14	47	0.847
	50	1.583		21	0.621	15	50	0.852
	55	1.425		22	0.661	16	53	0.854
	60	1.266		23	0.702	17	56	0.852
	65	1.108		24	0.745	18	59	0.846
	70	0.950		25	0.791	22	68	0.845
	75	0.791		26	0.840	25	73	0.855
	80	0.633		27	0.891	30	80	0.848
	85	0.475		28	0.944	31	81	0.853
	90	0.317		29	1.001	33	83	0.855
	95	0.158	30	1.060	34	84	0.851	

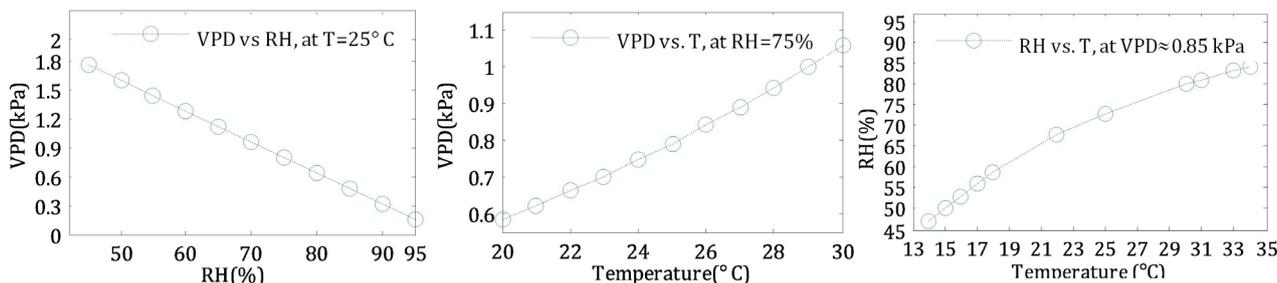


Fig. 4. Demonstration of *VPD* in relation to variable and constant *T* and *RH*.

VPD values decreased from 1.4 to 0.8 kPa, leading to an increase in the net photosynthetic rate, and to 17.3% average biomass and 12.35% yield increases. The same study also showed that during the winter season, the greenhouse *VPD* of approached 1.0 kPa in the absence of fogging in the middle of the days. Studies also show that using micro-fog systems for *VPD* control during the summer season can effectively enhance the growth and productivity of tomato, and can result in a substantial biomass and yield increase by improving photosynthesis (Zhang *et al.*, 2015). What is more, increasing air temperature by 2 °C in the winter season, in the hours of high humidity, is recommended to maintain optimal *VPD* (Sato *et al.*, 2000). However, pollen development may be reduced in the summer season if air temperature is too high (Sato *et al.*, 2000; Peet *et al.*, 2003). Portree (1996) reported a similar effect with too low air temperature at night hours (below 16°C), recommending a possible compensation with day temperatures. The increase in air temperature caused by a greenhouse environment (compared with an open environment) depends on the characteristics of the covering material, wind velocity, intensity of solar radiation and the transpiration of tomato plants. While day temperatures are significantly higher in greenhouses than in an open environment, night temperatures are only increased by 2 to 4°C, or in some cases, they are even lower than under open-field conditions (thermal inversion). Reports of an experimental study (Shamshiri *et al.*, 2016b) with two empty research greenhouses, one covered with polyethylene film without a climate control system, and the other with polycarbonate panels and with an evaporative cooling system, showed that while the *T* and *RH* of the outside air were, respectively, between 25-35°C and 55-95%, the inside microclimate reached *T*=68-70°C and *RH*=26-79% for the polyethylene greenhouse, and *T*=25-40°C and *RH*=47-93% for the polycarbonate greenhouse, with averaged maximum *VPD* of 13.6 and 3.9 kPa, respectively. Plots of 24 h average data for this experiment are shown in Fig. 5 and reveal that both temperatures and *VPD* are slightly affected by the greenhouse environment during night hours.

PRODUCTION CONSTRAINTS WITH ADVERSE MICROCLIMATE

Effects of suboptimal temperature

Shoot dry matter content and partitioning of tomato are affected by temperatures (Adams *et al.*, 2001). Indeed, tomato crops that suffer from heat stress have yields that are expected to decrease by 12.6% for every 1.2°C increase in temperature above 25°C, assuming that yield has a non-linear response, and the optimum and failure temperature are 23.5 and 30°C, respectively (Sato *et al.*, 2000). Air temperature higher or lower than the optimal values affects different phases of growth and development of tomato, as well as the overall fruit appearance and quality (Van Ploeg and Heuvelink, 2005). Baudoin *et al.* (2013) reported that when test plants were subjected to a persistent temperature below 10-12°C for several days, their productivity was affected. Moreover, it was observed that in low *RH* condition, air temperature above 30°C, and in high *RH* condition, temperature above 30-35°C reduces tomato productivity (Baudoin *et al.*, 2013). High temperatures cause fruit abortion and flaccid leaves because of improper transpiration, and can even destroy the plant. Tomato plants are notably sensitive to above-optimal air temperatures during the reproductive stage and may face a reduction in the percentage of fruit set, which triggers a significant yield decrease in commercial cultivation. In a study on the possible relationship between the reproductive stage of tomato and the average daily air temperature (Harel *et al.*, 2014), it was found that fruit number, the percentage of fruit set and fruit weight per plant decreased along with air temperature increase from 25 to 29°C. When temperatures are high, plants tend to transpire more. In such situations, yield reduction is mainly caused by the impaired pollen, another development and reduced pollen viability (Sato *et al.*, 2006). Values higher than 35°C will also reduce fruit set and delay the development of normal fruit colours (Jones, 2013). During the late maturation growth stage, tomato fruits also become more sensitive to high temperatures, and the rates of fruit growth volume are affected. Moreover, a high air temperature combined with too low *RH* values induces flower abortion.

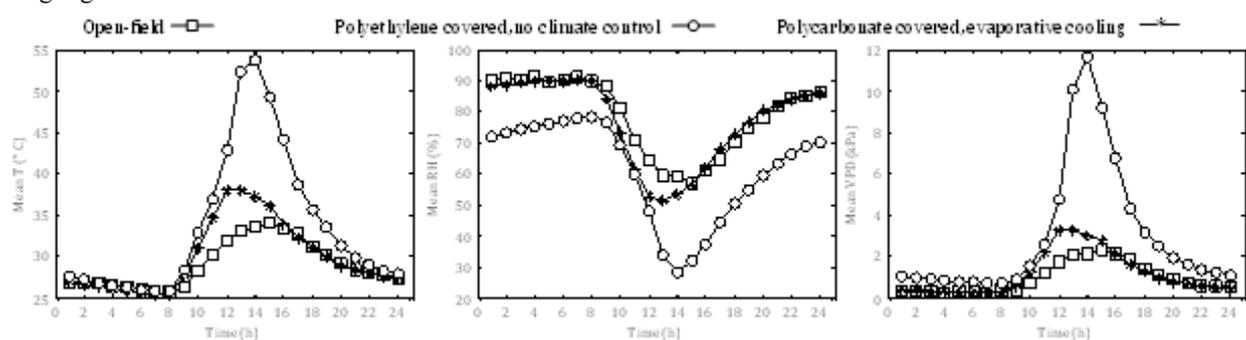


Fig. 5. Effects of greenhouse cladding and cooling systems on day and night *T*, *RH* and *VPD* under tropical climate conditions (Shamshiri *et al.*, 2016b).

Adams *et al.* (2001) reported that air temperature regimes lower than 14°C and higher than 26°C brought about small parthenocarpic fruits combined with low flower numbers and poor fruit set, resulting in decreased yields. Air temperature below 10°C was also shown to delay germination of seeds, inhibit vegetative development, shrink fruit set and impair fruit ripening (Jones, 2013). De Koning (1994) also reported that the mature fruiting growth stage was extended in treatments with low temperatures. In addition, in temperatures below 12.7°C, especially during night hours, tomato blossom drop will occur. Indeed, no significant growth and development in tomato plants were observed by Criddle *et al.* (1997) below an average temperature of 12°C. Still, Khayat *et al.* (1985) concluded that the effects of sub-optimal air temperature on tomato yields also depended on the cultivar. For example, while an average night air temperature of 12°C resulted in 76% of the yield obtained at 18°C for the 'Moneymaker' cultivar, it did not affect the growth of the 'Cherry' cultivar. Van Ploeg and Heuvelink (2005) also reported that chilling temperatures had negative effects on respiration and photosynthesis, and caused hormone imbalance in the plants. What is more, an average temperature of 14°C was found to result in smaller and harder tomato fruits with no marketable value (Adams *et al.*, 2001). In addition, tomato plants exposed to cool air temperatures below 18.3°C for long hours would flower profusely, with their flower clusters growing at the terminals (Jones, 2013). Vanthoor *et al.* (2011) noted that an average low temperature between 13 and 15°C may have positive effects on yield, but only at lower light levels. For example, with a low light condition of 7.6 MJ m⁻² day⁻¹, an average night temperature of 13.2°C increased tomato yield to 108% in relation to that obtained in 15.2°C, while no significant effect, in terms of yield increase, was observed under higher light conditions of 9.4 MJ m⁻² day⁻¹. However, the reviewed literature suggests that as air temperature increases from 18 to 29°C, the fruit growth period decreases approximately from 70 days to 40 days, while both yield and quality are improved, having their optimum values between 24 and 27°C.

Effects of suboptimal humidity

Various parameters, including the photosynthetic rate, morphology, yield and disease occurrence, are affected by greenhouse *RH*. Recommendations indicate that tomato grows better in relatively dry air. Liu *et al.* (2006) observed that *RH* between 55 and 90%, (corresponding to *VPD* of 0.2 and 1.kPa) does not have any negative effects on photosynthesis. In contrast, too much *RH* can stop transpiring and may result in turgor losses in plants. Indeed, Huang *et al.* (2011) found that, in comparison to 30-40% *RH*, pollen and fertilization of tomato was improved in *RH* between 60-70%. However, *RH* higher than 90% may increase pollen susceptibility to heat stress (Nepi *et al.*,

2010). In a highly humid greenhouse environment, diseases and fungal pathogens spread rapidly and infect plants. In tropical climate, pests and diseases spread faster due to high temperatures and humidity. Some of the diseases and physiological abnormalities associated with high humidity in greenhouse production include black spot, powdery mildew, leaf-edge burn in poinsettia and blossom-end rot of tomatoes. Other than that, plants evapotranspiration may be limited. Blossom end rot is partially related to low transpiration rates, and may be more likely to occur when *RH* is high. Moreover, calcium deficiency in tomato leaves is reported to be associated with high humidity and reduction of leaf area (Holder and Cockshull, 1990). Choi *et al.* (1997) reported that tomato fruit quality was reduced by high 24 h average humidity, while leaf area and shoot dry weight increased with high night humidity. Concentrations of nitrogen, phosphors, potassium, calcium and magnesium have been reported to decrease under high night humidity, with the calcium content in younger leaves being the most severely affected (Triguini *et al.*, 1999). Other problems associated with high and low temperatures and *RH* values were extensively discussed by Cohen *et al.* (2005). Detailed effects of humidity on tomato growth and production can be found in the works of Barker (1990) and Triguini *et al.* (1999). The following effects of high *RH* have been reported: disease and fungal pathogens spreading, disease occurrence (including black spot, powdery mildew, leaf-edge burn in poinsettia and blossom-end rot), low transpiration rates, blossom end rot, nitrogen, phosphors, potassium, calcium and magnesium deficiency, reduced fruit quality, increased leaf area and shoot dry weight.

Effects of suboptimal vapour pressure deficit

Various effects of high *VPD* on tomato fruit quality, growth and transpiration are discussed in the work of Leonardi *et al.* (2000). *VPD* directly affects water uptake by tomato plants and the overall tomato fruit yield. What is more, extremely high or low *VPD* values can result in leaf physiology disorders and development failure (Gautier *et al.*, 2001). Values of *VPD* larger than 1.0 kPa show the potential of air for holding more water vapour, enabling plants to transpire more. A low *VPD* indicates that e_s is very close to e_a . When *VPD* is zero ($e_s = e_a$), plants can hardly transpire. At a constant temperature, low and high *VPD*, respectively, indicate high and low levels of *RH* under greenhouse conditions. In a hot and humid tropical climate, low *VPD* rapidly leads to condensation dripping from the greenhouse cover (Shamshiri *et al.*, 2014), causing fungal spore contamination. Mineral deficiencies also appear due to low sap movement in the plant. Evaporative pad-and-fan systems can cause low *VPD* in tropical greenhouses by increasing *RH* without significantly reducing air temperature, and accelerate the spread of fungal diseases (Xu *et al.*, 2015). In arid climate conditions, improper environment

control of greenhouse can result in high *VPD* between 3-5 kPa, which leads to poor growth because tomato plants roots cannot compensate for the transpired water, thus, blossom-end rot and stomatal closure are likely to occur. Shamshiri *et al.* (2014) showed that maintaining an optimum *VPD* caused the hourly water uptake rate to increase by 35 to 50%. Furthermore, they noted that increases in water uptake, up to 800 ml plant⁻¹ d⁻¹, led to a higher crop yield. It should be underlined that tomato plants stop transpiring water into the air as a result of low *VPD*, causing an increase in pressure within the plants. In a study of the *VPD* effect in the range of 0.35-1.0 kPa in daytime, and 0.2-0.7 kPa in night time, Barker (1990) showed that low *VPD* reduced the leaf area index due to calcium deficiency, as well as average fruit weight and final yield, while increasing stomatal conductance. Because calcium moves through the xylem, it is affected by transpiration. Calcium deficiency leads to blossom end rot, especially in the presence of other stress factors (Barker, 1990; Holder and Cockshull, 1990). In addition, high solar radiation generates excessive transpiration and more accumulation of calcium in tomato leaves than in the fruits. Plant transpiration may be blocked at low *VPD* which influences the energy balance of the canopy. Fungal pathogens and mineral deficiency symptoms appear below a *VPD* value of 0.43 kPa, and disease infection can be most damaging below a *VPD* value of 0.2 kPa. Janse and Welles (1984) observed that fruits that are grown at low *VPD* generally become softer more quickly, and have lower quality and shorter shelf life. Still, early tomato yield was increased by low *VPD* during daytime, however, both day and night low *VPD* values reduced final yield and average fruit quality (Holder and Cockshull, 1990). In contrast, lower *VPD* values cause larger and thicker leaves and stems, and they weaken the root system as a result of efforts to compensate restricted transpiration. Reports of several studies indicate that *VPD* values below 0.2 kPa or above 2.2 kPa, respectively, representing highly humid and too dry greenhouse environments, increase the risk for fungal pathogen spreading and physiological disorders in tomato plants. In summary, low *VPD* values (below 0.3 kPa) in tomato plants cause mineral deficiencies, guttation, fungal diseases and soft growth, while high *VPD* (larger than 1.5 kPa) results in wilting, lear roll, stunted plants and crispy leaves.

RECAPITULATIONS

The aim of this paper was to review and summarize the optimal values of air and root-zone temperature, relative humidity and vapour pressure deficit for successful greenhouse cultivation of tomato. These values were gathered from extensive research publications on the physiology of greenhouse tomato, with the goal of simultaneously achieving high yield and high-quality fruit. The application of a decision-support system was highlighted in determining how close greenhouse microclimate parameters are to

the optimum condition, and how changes in each variable may affect the final yield. The presented approach can be used in a cost-benefit analysis for providing the best management decisions related, *inter alia*, to site selection, optimum growing season, scheduling efficiencies, energy management with different climate control systems, and risk assessments associated with each task. Effects of each parameter on the fruit quality and yield, and the associated problems with suboptimal values, were reviewed and summarized. It can be concluded that the effects of high or low temperatures may vary with different levels of humidity, light condition, intensity of solar radiation and CO₂ concentration. However, a decreasing trend in total fruit weight can be observed, assuming the average levels of other parameters. Both results of this review and the summarized values can be used in task planning algorithms for hierarchical decomposition of microclimate management and tomato growth models. The review can also contribute to generating the best economic models of tomato for energy conservation and energy efficient greenhouse crop productions. The cost of an increased automation level, relative to an increase in profitability, is a key consideration and should form part of future studies to justify the implementation of a greater level of automation.

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