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Dynamic Assessment of Air Temperature for Tomato (*Lycopersicon esculentum* Mill) Cultivation in a Naturally Ventilated Net-Screen Greenhouse under Tropical Lowlands Climate

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ABSTRACT

Net-screen covered greenhouses operating on natural ventilation are used as a sustainable approach for closed-field cultivation of fruits and vegetables and to eliminate insect passage and the subsequent production damage. The objective of this work was to develop a real-time assessment framework for evaluating air-temperature inside an insect-proof net-screen greenhouse in tropical lowlands of Malaysia prior to cultivation of tomato. Mathematical description of a growth response model was implemented and used in a computer application. A custom-designed data acquisition system was built for collecting 6 months of air-temperature data, during July to December 2014. For each measured air-Temperature (T), an optimality degree, denoted by $Opt(T)$, was calculated with respect to different light conditions (sun, cloud, night) and different growth stages. Interactive three-dimensional plots were generated to demonstrate variations in $Opt(T)$ values due to different hours and days in a growth season. Results showed that air temperature was never less than 25% optimal for early growth, and 51% for vegetative to mature fruiting stages. The average $Opt(T)$ in the entire 6 months was between 65 and 75%. The presented framework allows tomato growers to automatically collect and process raw air temperature data and to simulate growth responses at different growth stages and light conditions. The software database can be used to track and recor $Opt(T)$d values from any greenhouse with different structure design, covering materials, cooling system, and growing seasons and to contribute to knowledge-based decision support systems and energy balance models.

Keywords: Greenhouse, Growth response, Natural ventilation, Optimal Temperature, Tomato.

INTRODUCTION

High demands for quality agricultural products necessitate practicing innovative management techniques in different scopes of controlled environment plant production systems. Temperate crops such as tomato (*Lycopersicon esculentum* Mill) are successfully grown in the highlands of Malaysia, but local production is still insufficient in lowlands to meet the large market demands due to complications in environmental control, technology adoption, poor management, insufficient financial resources and software/hardware illiteracy of local growers. Greenhouse production of tomato in Malaysia has significant potentials in terms of economic and year-round

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production capability with increased productivity; however, the above mentioned problems have resulted in average tomato yield of 80 tons ha^{-1} (7.2 kg m^{-2}). Ambient air temperature inside conventional greenhouses in tropical lowland regions is a major issue in providing a comfortable growth condition. The excess heat imposed by direct solar radiation causes significant increase in the inside air temperature that is 20 to 30°C higher than the outside (Kittas *et al*., 2005; Xu *et al*., 2015). In addition, extended period of high air temperature limits plants evapotranspiration, causing tomato plants to wilt as a result of drawing inadequate water through roots system. Reports of an experimental study with an empty research greenhouse covered with polyethylene film showed that while Temperature (T) and Relative Humidity (RH) of outside air were, respectively, between 28-33°C and 70-85%, the inside microclimate reached T= 68-70°C, and RH= 20-35%, leading to air Vapor Pressure Deficit (VPD) between 18 and 21 kPa (Shamshiri *et al*., 2014a). Temperature values higher than 30°C cause fruit abortion and flaccid leaves because of insufficient transpiration (zero growth response), and subsequently eliminate possibilities of a successful production. The optimum air temperature for tomato during leaf/truss development is recommended at 22°C, for fruit addition 22-26°C, for fruit growth 22-25°C and for fruit-set 26°C (Sato *et al*., 2000; Adams *et al*., 2001).

In addition to the mentioned problems, tomato production in Malaysia can be significantly damaged by the *Yellow Leaf Curl* virus that is spread through Thrips and Aphids. Insect-proof net screen film greenhouses have been used for protected cultivation of fruits and vegetables against different damaging pests, such as Thrips and Aphids. They reduce open-field production risk and failures caused by heavy rain and hail, extreme solar radiation and high wind speed. Both anti-Thrips and anti-Aphid nets reduce air flow for ventilation, influence microclimate and cause sharp increases in the inside air temperature with negative consequences for crop development. Experimental and analytical models for determination of ventilation rate in greenhouses with insect-proof net-screen mesh films are available in the works of Desmarais (1997), Zhao *et al*. (2001); Tanny *et al*. (2003); Molina-Aiz *et al*. (2009) and Rigakis *et al*. (2015). Dynamic properties, geometric characterization, dimensions, resistance of net-screen films and the resulting microclimate environment have been studied using experimental approaches, mathematical models, and computer simulation software (Muñoz *et al*., 1999; Fatnassi *et al*., 2003; Möller *et al*., 2004; Shilo *et al*., 2004; Soni *et al*., 2005; Fatnassi *et al*., 2006; Katsoulas *et al*., 2006; Sethi *et al*., 2009; Alvarez *et al*., 2012; Villarreal *et al*., 2012; Tamimi *et al*., 2013; López-Martínez *et al*. 2013; Fatnassi *et al*., 2013; López-Martínez *et al*., 2014). A comprehensive review and discussion about insect-proof screen covered greenhouses is available in the work of Teitel (2007).

Malaysian growers are attempting to improve indoor climate of their greenhouses by practicing innovative concepts of clean-energy (Dieleman, 2011), for shifting from energy consuming (i.e., pad-and-fan controlled environments) to energy neutral greenhouses (shading and natural ventilation). Studies about different environmental control strategies indicates that smart management of natural ventilation for reducing temperature stress under hot and humid climate can be an effective approach that results in a more energy efficient production, with suitable growth condition and lower environmental impact (Dayan *et al*., 2004; Gruber *et al*., 2011). Improvements of closed-field plant production environment, however, require assessment models and knowledge-based information for long-term risk management by accurately determining interactions between climate parameters and growth responses. This study aimed to highlight potentials of natural ventilation in providing optimal air temperature in an insect-proof net-screen greenhouse under tropical lowlands climates of Malaysia by introducing a precise and reliable analysis framework based on a peer-reviewed published growth response model that determines real-time optimality degree for air temperature inside a greenhouse environment. This tool can help greenhouse growers to balance between available resources and their expectation from producing the best crop. Such results can contribute to energy consumption models (Abdel-Ghany *et al*., 2016; Ntinas *et al*., 2014, Khoshnevisan *et al*., 2015a and Khoshnevisan *et al*., 2015b) to determine the relationship between energy demand of different cooling systems as inputs and crop yield as output (Pahlavan *et al*., 2012).

MATERIALS AND METHODS

Model Description

The research methodology is based on a growth response model developed and extended by the Ohio Agricultural Research and Development Center (El-Attal, 1995; Ivey *et al*., 2000; Short *et al*., 2001; Short *et al*., 2005). This model defines optimality degree of air temperature for tomato production with independent membership-function Growth Response (GR) plots that are specific for different Growth Stages (GSs) and three light conditions (night, sun, cloud). The original model was described by means of several triangular and trapezoidal plots, representing membership functions, with input spaces (air temperature, denoted by T) that are referred to as the universe of discourse. Model developers explained that these plots were unique, and that the knowledge behind them were condensed from extensive scientific literature and peer-reviewed published research on greenhouse tomato production and physiology, with the goal of simultaneously achieving high yield and high quality fruit. For this model, Short *et al.* (1998) identified five growth stages for tomato as: (i) Germination and early growth with initial leaves (GS_1, 25 to 30 days); (ii) Vegetative (GS_2, 20 to 25 days); (iii) Flowering (GS_3, 20 to 30 days); (iv) Early fruiting (GS_4, 20 to 30 days), and (v) Mature fruiting (GS_5, 15 to 20 days). The exact days within each stage depends on crop varieties and other environmental factors such as air temperature and light condition. Some varieties have been hybridized to specific climate or might be more sun tolerant that makes their fruit production time shorter. The average duration to reach mature fruiting stage for most greenhouse tomato varieties is between 65 and 100 days depending on the breeds. For an early variety, the approximate time to maturity is between 50 to 65 days, and for a late variety it is 85 to 95 days (Jones and Benton, 2007). The days from seeding to first fruit harvest, varies from 45 days to over 100 days (Jones and Benton, 2007).

Model Implementation

Mathematical expression of the model was written in a way that a membership function for specific growth stage and light condition on the universe of discourse be defined as $f\left(T_{m,n}\right)_{GS,(Light)}: T_{m,n} \rightarrow [0,1]$, where air temperature readings at time $t_{m,n}$ are mapped to optimality-degree values, denoted by $Opt(T)$, between 0 and 1. The two indexes m and n refer to specific minute and date of a time reading in the framework database. A sample representation of these membership functions is provided in Figure 1 (left) for vegetative to mature fruiting Growth Stage ($GS_{2\text{-}5}$) at night condition. This demonstration shows that temperature values between 18 and 20°C correspond to optimal growth response (or $Opt(T) = 1$). A wider temperature border, i.e., 14.3 to 34°C, associates with a lower growth response, $(0.3 \leq Opt(T) \leq 1)$. In this particular example, a greenhouse air temperature equal to 34 °C at night hours is 30% optimal for

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tomato in its vegetative to mature fruiting growth stage. It should be noted that in this model, an optimality-degree equal to 1 refers to a potential yield with marketable value, which is a function of both harvested mature weight per unit area and high quality fruit. The analysis framework shown in Figure 1 (right) (Shamshiri *et al*., 2014b) with input-output architecture was programmed in MATLAB environment (The MathWorks Inc, Natick, MA, USA) as a software platform for interfacing with the model. The marginal and optimal set-points of air temperature, corresponding to growth response of 0 and 1, were precisely determined from graphical representations of the original model. These values are summarized in Table 1 for further references. Mathematical descriptions of the entire membership functions are provided in Table 2. The organization of these functions are as follow: one function for air temperature at the early Growth Stage (GS_1) and for all light conditions, denoted by

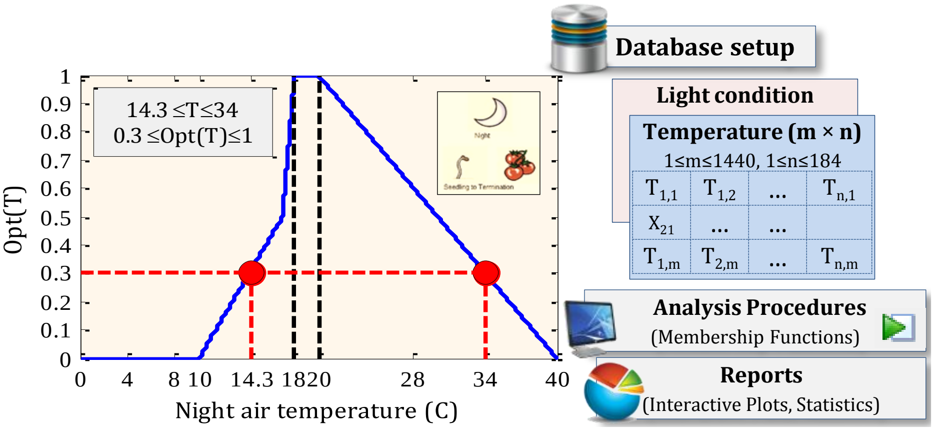

Figure 1. Sample plot of the implemented model, demonstrating tomato's growth response to air temperature at vegetative to mature fruiting growth stage in night condition (left) and schematic diagram illustrating input-output architecture of the analysis framework.

Table 1. Marginal and optimal reference values of air temperature at different growth stages and light condition.

GS	Temperature		Description
	Reference Border	Value (°C)	
Stage 1	$T1_{G0,min}$	9	Lower marginal temperature for growth stage 1, (all lights)
	$T1_{G0,max}$	35	Upper marginal temperature for growth stage 1, (all lights)
	$T1_{G1,min}$	24	Lower optimal temperature for growth stage 1, (all lights)
	$T1_{G1,max}$	26.1	Upper optimal temperature for growth stage 1, (all lights)
Stage 2 to 5	$T2_{G0,min}$	10	Lower marginal temperature for growth stage 2-to-5, (all lights)
	$T2_{G0,max}$	40	Upper marginal temperature for growth stage 2-to-5, (all lights)
	$T2_{G0.5,(night)}$	17	Reference temperature for GR=0.5, growth stage 2-to-5, (night)
	$T2_{G1,\min(night)}$	18	Lower optimal temperature for growth stage 2-to-5, (night)
	$T2_{G1,\max(night)}$	20	Upper optimal temperature for growth stage 2-to-5, (night)
	$T2_{G1,\min(sun)}$	24	Lower optimal temperature for growth stage 2-to-5, (sun)
	$T2_{G1,\max(sun)}$	27	Upper optimal temperature for growth stage 2-to-5, (sun)
	$T2_{G1,\min(cloud)}$	22	Lower optimal temperature for growth stage 2-to-5, (cloud)
	$T2_{G1,\max(cloud)}$	24	Upper optimal temperature for growth stage 2-to-5, (cloud)

$Opt(T)_{stg1(All\ Lights)}$, and three functions, for sun, night, and cloud conditions at the vegetative to mature fruiting Growth Stage ($GS_{2\text{-to-}5}$), denoted by $Opt(T)_{stg2-5(sun)}$, $Opt(T)_{stg2-5(night)}$, and $Opt(T)_{stg2-5(cloud)}$, respectively. These functions, together with the reference values in Table 1, were integrated in the analysis framework and were used for generating reports.

Data Collection

A custom-designed data acquisition system was built for the purpose of collecting the required data from the greenhouse environment and to provide local growers with an affordable hardware interface. Three temperature sensor modules, including, two digital SHT11 and SHT15 sensors (Sensirion, AG, Switzerland) and one analog HSM-20G

Table 2. Membership functions growth response model for optimality of air temperature in cultivation of tomato at different growth stages and light conditions.

Membership Functions	Universe of discourse
$Opt(T)_{stg1(All\ Lights)} = \begin{cases} 0 \\ \dfrac{T - T1_{G0,min}}{T1_{G1,min} - T1_{G0,min}} \\ 1 \\ \dfrac{-(T - T1_{G0,max})}{T1_{G0,max} - T1_{G1,max}} \\ 0 \end{cases}$	$T < T1_{G0,min}$ $T1_{G0,min} \le T < T1_{G1,min}$ $T1_{G1,min} \le T \le T1_{G1,max}$ $T1_{G1,max} < T \le T1_{G0,max}$ $T > T1_{G0,max}$
$Opt(T)_{stg2-5(sun)} = \begin{cases} 0 \\ \dfrac{T - T2_{G0,min}}{T2_{G1,\min(sun)} - T2_{G0,min}} \\ 1 \\ \dfrac{-(T - T2_{G0,max})}{T2_{G0,max} - T2_{G1,max(sun)}} \\ 0 \end{cases}$	$T < T2_{G0,min}$ $T2_{G0,min} \le T < T2_{G1,\min(sun)}$ $T2_{G1,min(sun)} \le T \le T2_{G1,max(sun)}$ $T2_{G1,max(sun)} < T \le T2_{G0,max}$ $T > T2_{G0,max}$
$Opt(T)_{stg2-5(night)} = \begin{cases} 0 \\ \dfrac{0.5(T - T2_{G0,min})}{T2_{G0.5,(night)} - T2_{G0,min}} \\ \dfrac{0.5(T - T2_{G0,min})}{T2_{G0.5,(night)} - T2_{G0,min}} \\ 1 \\ \dfrac{-(T - T2_{G0,max})}{T2_{G0,max} - T2_{G1,max(night)}} \\ 0 \end{cases}$	$T < T2_{G0,min}$ $T2_{G0,min} \le T < T2_{G0.5,(night)}$ $T2_{G0.5,(night)} \le T < T2_{G1,min(night)}$ $T2_{G1,\min(night)} \le T \le T2_{G1,max(night)}$ $T2_{G1,max(night)} < T \le T2_{G0,max}$ $T > T2_{G0,max}$
$Opt(T)_{stg2-5(cloud)} = \begin{cases} 0 \\ \dfrac{T - T2_{G0,min}}{T2_{G1,\min(cloud)} - T2_{G0,min}} \\ 1 \\ \dfrac{-(T - T2_{G0,max})}{T2_{G0,max} - T2_{G1,max(cloud)}} \\ 0 \end{cases}$	$T < T2_{G0,min}$ $T2_{G0,min} \le T < T2_{G1,\min(cloud)}$ $T2_{G1,min(cloud)} \le T \le T2_{G1,max(cloud)}$ $T2_{G1,max(cloud)} < T \le T2_{G0,max}$ $T > T2_{G0,max}$

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(Shenzhen Mingjiada Electronics LTD, Futian Shenzhen, China) were directly connected to a microprocessor unit in order to minimize data collection errors and avoid possible hardware interruptions. The processing parts contained ATmega328P (Atmel®, San Jose, CA) microcontroller on the open source Arduino Uno prototyping platform programmable in Arduino sketch environment software with C language. This microcontroller was selected based on the prototype board availability, small size and inexpensive development cost that made it suitable for repeated trials. It should be noted that all vital components (i.e., clock generator, memory and power regulator) for operating the microcontroller, as well as directing programming and access to input/output pins were provided by the corresponding startup board. Major components on the startup board included: ATmega328 microcontroller operating at 5V with 2 KB of RAM, 32 KB of flash memory for storing programs, 1 KB of EEPROM for storing parameters, a 16 MHz crystal oscillator, digital input/output pins, USB connection, power jack, and a reset button. A micro Secure Digital (SD) card board was used for storing large sensor data. The prototype board was equipped with Liquid-Crystal Display (LCD) and serial port RS-232 communication cable (bidirectional with maximum baud speed up to 115200 bites per seconds) for transferring and storing collected data into personal computer. The final DAQ prototype package with sensors connections and other complementary components are shown in Figure 2 with labels referring to the following items: (a) LCD; (b) HSM20G sensor circuit connection; (c) Power supply; (d) Micro SD card board on top of Ardunino board; (e) Output connection; (f) Sensor input; (g) Relay circuit board, right picture, and (h) Final prototype package. The accuracy of temperature reading with this system is ± 0.1°C and its reliability has been confirmed with a control sample data collected by local weather station at Sultan Abdul Aziz Shah-Subang in Malaysia where day light condition (sun or cloud) data was provided. Air temperature sensors were placed 1 meter above the soil and were sheltered to reduce effects of direct solar radiation on the measurements. Sensor

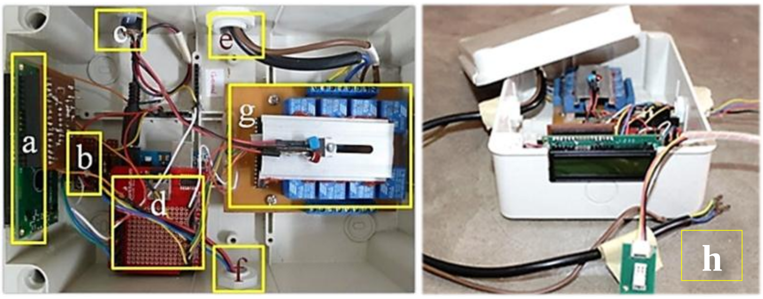

Figure 2. Custom-designed data acquisition system used in data collection with Arduino Uno microcontroller platform.

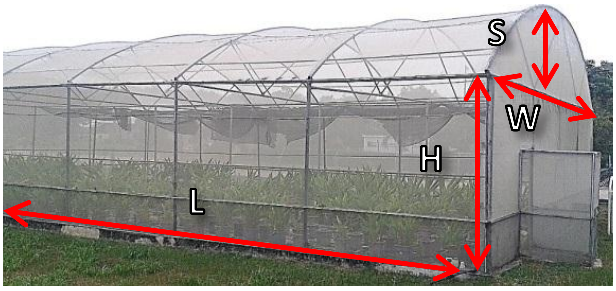

Figure 3. The insect-proof net-screen covered greenhouses under study**.**

readings were then set at 1 Hz frequency and were averaged over 60 seconds. Sample data were collected for a total of 184 days (1st of July to 30th of December, 2014) from an insect proof net-screen covered greenhouse shown in Figure 3 with west-east orientation, located at the campus of Universiti Putra Malaysia (Latitude= 3° 0' 9.8094" N and Longitude= 101° 42' 11.2926" E). The greenhouse structure was made of galvanized iron pipes frames covered with anti-Thrips polyethylene monofilaments net-screen film. Specification and properties of the cladding materials according to the supplier manual were as follow: Round mesh type of 50-by-25 per 0.0254 m; Hole size: 0.36 by 0.87 mm; Wire diameter: 150 μm; Weight: 0.06 kg m^{-2}; Air flow resistance: 11.1, Covering against light: 0.36, transparent color with 3% ultraviolet absorbance. The screenhouse dimensions were: Length=12 m; Width= 4 m; Walls height (H)= 2 m, and Sagitta (S)= 0.8 m.

RESULTS AND DISCUSSION

Results were entirely generated by the analysis framework and are expressed in terms of optimality-degree, $Opt(T)$, that are specific for two groups of growth stages according to the original model; (A) Early Growth Stage (GS$_1$), and (B) Vegetative to mature fruiting Growth Stages (GS$_{2\text{ to }5}$). Descriptive statistics of raw data were generated for each month and are reported in Table 3. Average outside air temperature in this study for the entire 184 days of experiment was 28.2 °C, which implies that collected data were relatively close to the optimal range of tomato requirements. This observation, however, does not imply that other methods of greenhouse cooling such as air conditioning or pad-and-fan evaporative cooling systems are not required in net-screen greenhouses. A profounder outlook from the descriptive statistics in Table 3 reveals that averaged-maximum air temperature inside

Table 3. Descriptive statistics of raw data for the entire 184 days.[a]

Month	Outside air temperature (°C)				Inside air temperature (°C)				Averaged solar radiation
	Avg	Std	Min	Max	Avg	Std	Min	Max	(MJ/m^2)
Jul	28.1	3.3	21.6	37.2	31.8	2.4	27.6	38.4	19.42
Aug	28.7	2.9	24.2	35.3	30.7	3.2	26.4	37.6	19.14
Sep	29.0	2.8	23.3	35.4	30.3	3.1	26.2	36.3	20.22
Oct	28.4	2.7	23.2	35.3	30.5	2.6	26.5	37.4	16.53
Nov	27.9	2.6	23.1	35.0	30.2	2.5	25.3	36.2	16.26
Dec	27.9	2.5	23.8	35.2	29.4	2.8	25.1	37.7	13.38
Avg	28.3	2.8	23.2	35.5	30.5	2.8	26.2	37.3	17.49

[a] Avg: Average, Std: Standard deviation.

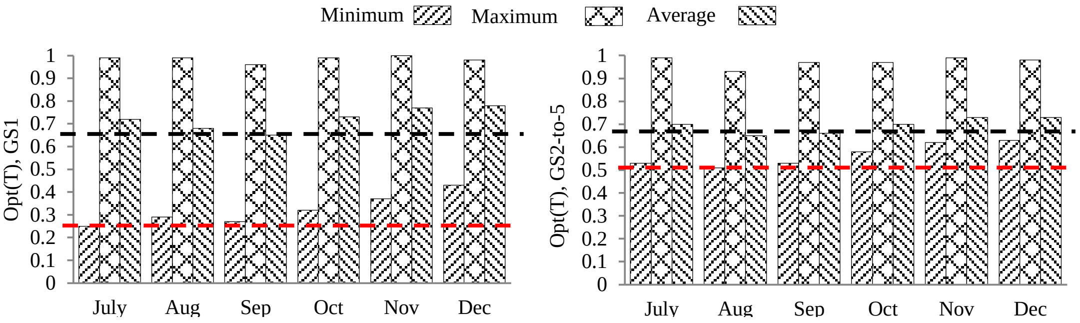

Figure 4. Comparison between minimum, maximum and average optimality degrees of air temperature for early growth stage (left) and vegetative to mature fruiting stage (right) of tomato.

the greenhouse is 37.3°C, an evidence of production failure because of significantly exceeding from upper-bounds of marginal air temperature values. According to the growth response model, marginal values are the minimum or maximum air temperature that tomato can tolerate before production fails. The maximum air temperature values in each day of data collection are associated with zero optimality-degree on the membership function model. Therefore, greenhouses require a method or combination of methods (i.e., shading, mechanical ventilating or even air conditioning) to control ambient temperature in these critical hours. Table 4 provides a summary of $Opt(T)$ results due to different hours, days, and months. Graphical comparison between minimum, maximum, and average $Opt(T)$ values of each month is demonstrated by two bar plots in Figure 4. The upper horizontal dashed-line (black color) shows that minimum average value for the entire 6 months was at least 0.65. This line can be used as a trigger to activate additional cooling systems (i.e., mechanical ventilation, evaporative cooling, or air conditioning) based on production preferences and objectives (i.e., whether tomato is produced for fresh consumption or for processing industries). The lower dashed-line (red color) represents lowest minimum value, which is an indication of the minimum potential of natural ventilation.

To provide a better inclusion on these results, graphical representation of averaged $Opt(T)$ values for each month are demonstrated in Figure 5-A for early Growth Stage (GS_1) and in Figure 5-B for vegetative to mature stage ($GS_{2\ to\ 5}$). An immediate observation from these results at GS_1 implies that all curves follow a sinusoidal pattern in the 24-hours. This trend in the averaged

Table 4. Hourly averaged optimality degree of air temperature at different growth stages from July to December, 2014.

Hours	Early Growth Stage (GS_1)						Vegetative to mature fruiting Growth Stage ($GS_{2\ to\ 5}$)					
	Jul	Aug	Sep	Oct	Nov	Dec	Jul	Aug	Sep	Oct	Nov	Dec
0:00	0.94	0.87	0.84	0.89	0.93	0.92	0.69	0.65	0.63	0.66	0.68	0.67
1:00	0.94	0.90	0.88	0.92	0.94	0.93	0.70	0.66	0.65	0.67	0.68	0.68
2:00	0.98	0.91	0.91	0.94	0.96	0.94	0.73	0.68	0.67	0.68	0.69	0.69
3:00	1.00	0.94	0.93	0.96	0.97	0.96	0.75	0.69	0.68	0.7	0.7	0.7
4:00	0.99	0.95	0.94	0.96	0.98	0.97	0.77	0.69	0.69	0.71	0.72	0.71
5:00	0.99	0.97	0.95	0.99	0.99	0.98	0.76	0.70	0.70	0.72	0.73	0.72
6:00	0.99	0.97	0.95	1.00	0.99	0.98	0.84	0.81	0.79	0.73	0.74	0.72
7:00	0.99	1.00	1.00	0.98	1.00	1.00	0.87	0.84	0.80	0.73	1.00	0.73
8:00	0.97	0.98	0.93	0.92	0.96	0.96	1.00	1.00	1.00	1.00	0.99	1.00
9:00	0.86	0.85	0.78	0.8	0.83	0.86	0.94	0.86	0.90	0.92	0.93	0.94
10:00	0.64	0.64	0.57	0.64	0.68	0.7	0.82	0.75	0.77	0.82	0.84	0.84
11:00	0.45	0.51	0.44	0.51	0.54	0.56	0.69	0.67	0.68	0.74	0.75	0.75
12:00	0.33	0.42	0.35	0.41	0.42	0.47	0.61	0.61	0.61	0.65	0.67	0.69
13:00	0.25	0.35	0.29	0.33	0.37	0.43	0.54	0.56	0.57	0.6	0.63	0.67
14:00	0.26	0.29	0.27	0.32	0.38	0.43	0.53	0.52	0.56	0.58	0.62	0.66
15:00	0.33	0.29	0.29	0.34	0.42	0.46	0.56	0.52	0.57	0.6	0.63	0.67
16:00	0.39	0.30	0.30	0.43	0.51	0.52	0.62	0.51	0.58	0.62	0.69	0.69
17:00	0.43	0.34	0.34	0.53	0.6	0.63	0.64	0.53	0.60	0.69	0.72	0.76
18:00	0.52	0.39	0.42	0.62	0.71	0.71	0.61	0.54	0.61	0.77	0.82	0.8
19:00	0.67	0.56	0.52	0.7	0.77	0.79	0.66	0.62	0.66	0.72	0.63	0.85
20:00	0.76	0.66	0.62	0.77	0.83	0.83	0.60	0.55	0.53	0.61	0.63	0.63
21:00	0.83	0.70	0.68	0.8	0.86	0.85	0.63	0.56	0.55	0.61	0.64	0.64
22:00	0.88	0.79	0.75	0.82	0.87	0.87	0.66	0.60	0.58	0.62	0.64	0.64
23:00	0.89	0.84	0.78	0.84	0.89	0.89	0.67	0.63	0.60	0.63	0.66	0.65
Min	0.25	0.29	0.27	0.32	0.37	0.43	0.53	0.51	0.53	0.58	0.62	0.63
Max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Avg	0.72	0.68	0.65	0.73	0.77	0.78	0.70	0.65	0.66	0.70	0.73	0.73
Std	0.27	0.26	0.26	0.23	0.22	0.20	0.12	0.12	0.11	0.10	0.11	0.09

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$Opt(T)$ values is only valid at GS$_1$ and can be described precisely by Fourier model, which is consistent with the trends in the average of raw temperature data due to the linearity and independency nature of the membership function at GS$_1$ to the input space. The information provided by Table 4 and plots of Figure 5 indicate that, during the entire 184 days, the averaged $Opt(T)$ values at early growth stage (GS$_1$) to mature fruiting (GS$_{2\ \text{to}\ 5}$) was between 0.65 and 0.78. The minimum $Opt(T)$ values were in the range of 0.25 to 0.43 (recorded in July and December, respectively) at the early Growth Stage (GS$_1$), and 0.51 to 0.63 (recorded in August and December, respectively) at vegetative to mature stage (GS$_{2\ \text{to}\ 5}$). This can be interpreted that, in the naturally ventilated greenhouse, $Opt(T)$ was about two times greater at the final four Growth Stages (GS$_{2\ \text{to}\ 5}$) compared with the early Growth Stage (GS$_1$). In fact, minimum $Opt(T)$ is an indication of the lowest tomato's growth response to air temperature, which can cause crop stress with significant effects on yield and development of fruits setting. These values are associated with critical hours in which maximum cooling is required. It should be noted that since this research was carried out for tropical lowlands, the minimum $Opt(T)$ values are obviously associated with maximum recorded air temperature, because it is very unlikely for air temperature in these regions to drop below a certain point that significantly affects growth response, and causes failure in production. In moderate or cold climate conditions however, minimum $Opt(T)$ values can be due to either high or low temperature hours. The averaged minimum temperature values in this study were in the range of 21.6 to 24.2°C, which shows that greenhouse environment was significantly far from lower-bounds of marginal borders (9 to 10°C), therefore, closed-field plant productions in tropical lowlands are not equipped with heating systems. The maximum $Opt(T)$ values were between 0.95 and 1, corresponding to the hours in which no cooling energy is required. This is the maximum potential of natural ventilation. It can be observed from Table 4 that for the net-screen greenhouse of this study, air temperature provided by natural ventilation during the hours associated with $Opt(T)_{max}$ was 100% ideal.

In order to provide an interactive graphical tool for navigation between different days and for long term track and record of air temperature data, a set of three-dimensional plots (Figure 6) was generated to simultaneously demonstrate trends in $Opt(T)$ values with respect to 24-hour time and days. The day's axis in Figure 6 is group-labeled by each data collection months. These plots can be used for instant demonstration of optimality-degrees at different hours, days, and months. In addition, they provide valuable information to explore $Opt(T)$ trends in a specific time

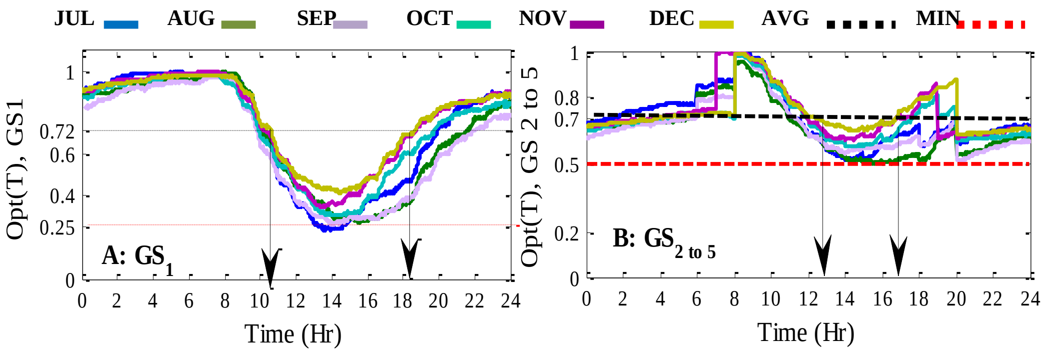

Figure 5. Demonstration of 24-hour monthly averaged optimality degrees of air temperature for early growth stage (left) and vegetative to mature fruiting stage (right) of tomato.

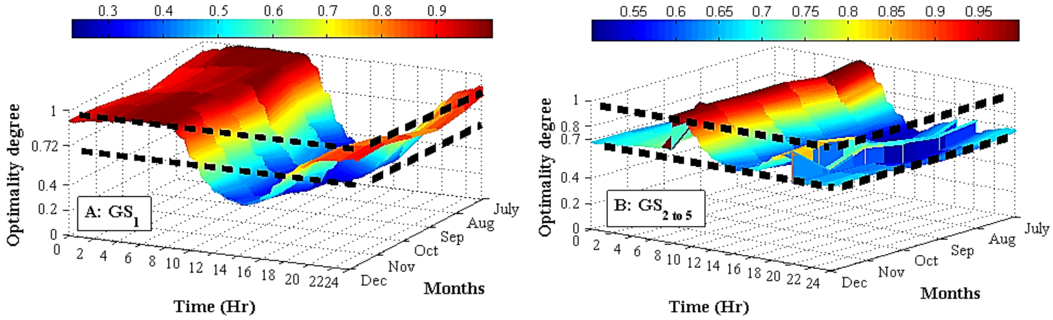

Figure 6. Interactive 3D plots demonstrating 24-hour trends in optimality degrees with respect to days and months.

frame and to compare it with a reference value of a temperature controller. For example, air temperature associated with the area inside the dashed-lines of Figure 6 can be considered acceptable, depending on production preferences and expectations. The lower dashed-line can serve as a trigger for air temperature control, and can be moved along the month's axis at a specific growth stage to display the exact time that maximum cooling is required. This user-interface allows navigating between the results to select and display a specific day for more in-depth enquiry. Results of such application are shown in Figure 7, for a random day, Date: 12/22/2014). Upon user's selection, the framework automatically creates 24-hour plot of raw data (Figure 7-a) followed by corresponding optimality degree plots for early growth stage (Figure 7-b) and vegetative to mature fruiting stage in Figure 7-c. The three colors in each plot are associated with three light conditions (black for night, red for sun, and blue for cloud). It can be observed that for this particular day, from 00:01 am to 8:00 am, while temperature was between 24 and 26°C (Figure 7-a), the optimality degree in that time frame was constantly equal to 1 for early growth (Figure 7-b), and between 0.7 to 0.8 for vegetative to mature fruiting growth stage (Figure 7-c). In other words, greenhouse air temperature during these 8-hours was 100% optimal for the first 25-30 days of tomato production, and 70 to 80% optimal for the rest of production period. From 8:00 am to 9:00 am, the optimality degree for the entire five growth stages was 1, before it declines to its lowest value of 0.4 for GS_1 at 1:00 pm (Figure 7-b), and 0.55 for $GS_{2\ \text{to}\ 5}$ at 2:00 pm (Figure 7-c). This result is consistent with that of Sato *et al*. (2000), who concluded that temperatures not exceeding 27°C are unlikely to reduce tomato production. A similar implicative approach can be extended to describe air temperature at different hours and days in different greenhouses.

CONCLUSIONS

In this paper, a systematic approach was presented for evaluation of air temperature in a naturally ventilated net-screen covered

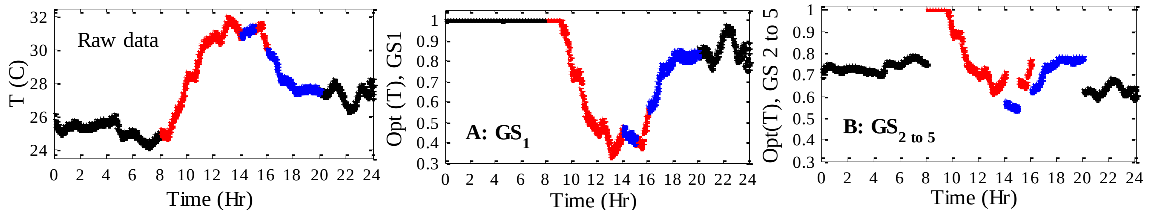

Figure 7. Demonstration of raw temperature data (top plot) versus optimality degree plots for early growth (left) and vegetative to mature fruiting growth stage (right). Results belong to a random day, Date: 12/22/2014.

greenhouse under tropical lowland climates of Malaysia. A real-time analysis framework with hardware-software interfaces was developed for collecting and processing raw data. Peer-reviewed published growth response model with membership-functions that describe optimality degree of air temperature for tomato production was implemented in the framework analysis procedure. Results were generated with respect to different growth stages and light condition. Interactive three-dimensional plots were introduced as a graphical tool for navigating between optimality degrees of temperature in different hours, days, months and growth stages. It was shown that during July to December, 2014, the average $Opt(T)$ for tomato production in the naturally ventilated net-screen greenhouse was between 65 and 75%. Decision about selecting a preferred level of optimality degree is based on environmental responses, control cost, production objectives (whether tomato is produced for fresh consumption or for processing industries), local market demands, and adaptability factors. The presented framework can assist greenhouse growers and research institutes to assess the effects of structure design, covering materials, cooling techniques and growing season on the optimality levels of microclimate temperature. It can also be used to evaluate climate condition prior to large scale greenhouse construction by contributing to management decisions such as scheduling efficiencies, site-selection, cooling cost estimation, and risk assessments associated with each task. A decision support system would benefit from this information to adjust inputs of an adaptive controller for renewable and sustainable environmental control techniques.

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ارزیابی دینامیکی درجه حرارت هوای داخل گلخانه توری با تهویه طبیعی برای کشت گوجه فرنگی در شرایط آب و هوایی زمین های پست استوایی

ر. شمشیری، پ. ون بی ورن ، ه. چه من ، و ع. ج. زکریا

چکیده

گلخانه های با پوشش توری و سیستم تهویه به عنوان روشی پایدار برای ایجاد محیط های بسته در کشت میوه و سبزیجات مورد استفاده قرار میگیرند تا از ورود آفات و خسارات به محصول جلوگیری کنند. هدف از این تحقیق طراحی و ساخت سیستم زمان–واقعی برای آنالیز و ارزیابی دمای هوا داخل گلخانه های توری تحت شرایط آب و هوای زمین های پست استوایی بود. برای این منظور نرم افزار کامپیوتری بر اساس مدل ریاضی

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رشد گوجه فرنگی که توسط دانشگاه ایالتی اوهایو ارائه و منتشر شده بود ساخته شد. به منظور ارتباط سخت افزاری با نرم افزار – یک سیستم اتوماتیک جمع آوری داده ساخته و توسط آن اطلاعات نور و دمای هوا هر دقیقه و به مدت ۶ ماه از تاریخ جولای تا دسامبر ۲۰۱۴ ثبت شد. داده ها بر اساس شرایط نور (آفتاب–ابر–شب) به صورت خودکار در نرم افزار پردازش شدند و به ازای هر داده ی دمای هوا – عددی به عنوان درجه اپتیم که با Opt(T) نشان داده میشود برای هر مرحله رشد محاسبه شد. پلات های سه بعدی با ویژگی ارتباط با کاربر برای نمایش تغییرات Opt(T) ناشی از ساعت و روزهای مختلف یک فصل رشد طراحی و استفاده شدند. نتایج پردازش اطلاعات نشان داد که کمترین میزان درجه اپتیمال دمای هوای داخل گلخانه برای مرحله اول رشد ۲۵٪ و برای مرحله سبزشدن تا برداشت محصول ۵۱٪ بود. میانگین درجه اپتیمال در کل ۶ ماه این تحقیق بین ۶۵ و ۷۵٪ بود. نرم افزار ارائه شده این امکان را به مدیران گلخانه میدهد که بدون نیاز به دانش کشاورزی و کامپیوتر – اطلاعات دمای هوای داخل گلخانه را برداشت و آنالیز کرده و عملکرد گوجه فرنگی در پاسخ به دمای هوا را قبل از کشت در هر مرحله از رشد و برای شرایط مختلف شبیه سازی کنند. همچنین بانک اطلاعاتی نرم افزار میتواند با ثبت و مقایسه مقادیر Opt(T) از گلخانه های با طراحی متفاوت یا پوشش و سیستم خنک کنندگی مختلف جهت توسعه سیستم های پشتیبانی تصمیم گیری مبتنی بر دانش و مدل های تعادلی انرژی مفید واقع شود.