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Measuring optimality degrees of microclimate parameters in protected cultivation of tomato under tropical climate condition

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ABSTRACT

The objective of this work was to integrate a membership function growth response model for measuring optimality degrees of air temperature (T) and relative humidity (RH) in a tropical greenhouse planted with tomato (*Lycopersicon esculentum*). Experiment was carried out during spring growing season of 2015, for a total of 147 days, in an insect-proof net-screen covered greenhouse in tropical lowlands of Malaysia. An analysis framework with a custom-designed hardware/software was developed for interfacing with the model and data processing. Raw data were separated into three groups of growth stages according to the original model, as early growth, vegetative growth, and flowering to mature fruiting growth stages. For each collected T and RH, an optimality degree denoted by $Opt(T)$ and $Opt(rH)$ with value between 0 and 1 was calculated. Preliminary results showed that maximum T and RH belong to the mature fruiting stage (39.7 °C and 98.9%), and were recorded respectively at sun and cloud light conditions. The minimum and maximum values of $Opt(T)$ were equal to 0.16 and 0.95 at the early growth stage, 0.42 and 0.92 at the vegetative stage, and 0.27 and 0.75 at the flowering to mature fruiting stage. These values for $Opt(RH)$ were 0.62 and 1, 0.31 and 0.9, and 0.46 and 1, respectively. Further analysis of results showed that comparison between averaged optimality degrees in different light conditions (night, sun, cloud) depends on the specific growth stage. For example, during early growth stage, night hours had the highest $Opt(T)$ and $Opt(RH)$, while at the vegetative growth stage, $Opt(T)$ did not vary significantly with light conditions. The presented framework contributes to knowledge-based information in greenhouse climate control and management by measuring optimality degrees for addressing specific hours, light conditions and growth stages associated with maximum and minimum cooling requirements.

1. Introduction

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

Air temperature (T) inside conventional tropical greenhouses with polyethylene covering materials and evaporative cooling systems is a major issue in providing comfortable growth condition for tomato. The excess heat imposed by direct solar radiation causes substantial amount of increase in the inside air temperature that is 20 to 30 °C higher than the outside [1,2]. 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 [3]. It also leads to fruit abortion and flaccid leaves because of insufficient transpiration. Experiments with a polyethylene film covered greenhouse 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 to T = 68–70 °C, and RH = 20–35%, leading to air vapor pressure deficit (VPD) between 18 and 21 kPa [4]. Such a microclimate condition corresponds to zero growth response for tomato and subsequently eliminates any chances of a successful production.

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Insect-proof (anti-Thrips and anti-Aphid) net screen film greenhouses operating on natural ventilation have been proposed as a sustainable approach for protected cultivation of fruits and vegetables and to eliminate insect passage and subsequent production damage. While these structures reduce open-field production risk and failures caused by heavy rains, hail, and extreme solar radiation, they also restricts air flow for ventilation, causing sharp increases on the inside air temperature with negative consequences for crop development. It is therefore of interest to evaluate comfort level of microclimate parameters in these greenhouses for possible improvements and managements. Experimental and analytical models for determination of ventilation rate in greenhouses with insect-proof net-screen mesh films are available in the works of [5–11]. Dynamic properties, geometric characterization, dimensions, air resistance of net-screen films and the resulting microclimate environment have been studied using experimental approaches, mathematical models and computer simulation software [12–25]. A comprehensive review and discussion about insect-proof screen covered greenhouses is available in the work of [26].

Sustainable development of greenhouse production requires site specific information for adaptive management of resources in order to reduce production cost and increase profit. This study was motivated by the demands for reducing high cost of greenhouse cooling in tropical lowlands regions and to investigate possible techniques for shifting from energy consuming to energy neutral greenhouses. Monitoring and evaluating plant's growth microclimate at different stages of its life cycle is the first step toward this objective. This paper introduces a framework for measuring optimality degrees of microclimate parameters using a peer-reviewed published tomato growth response model [27]. A computer application was developed for interfacing with the model and for immense data processing. Results of measurements describe how close the plant production environment is to the optimal growth condition with respect to a specific growth stage, light condition (sun, cloud, night), and hour of the day.

2. Materials and methods

2.1. Model description

The research methodology is based on a growth response model extended by the Ohio Agricultural Research and Development Center [27] for decision support in greenhouse climate control. This model defines optimality degrees of air temperature (T) and relative humidity (RH) for tomato production with independent trapezoid membership-function growth response (GS) plots that are specific for different growth stages and three light conditions (night, sun, cloud). These plots were originated from the work of [28] using utility theory with the goal of simultaneously achieving high yield and high quality fruit. According to [27,28], the knowledge behind these plots was condensed from extensive scientific literature and peer-reviewed published research on greenhouse tomato production and physiology. The model identifies five growth stages for tomato as (i) early growth with initial leaves, (ii) vegetative growth stage, (iii) flowering and fruit set stage, (iv) fruit formation and early fruiting stage, and (v) mature fruiting stage. In this paper, we refer to these growth stages as GS_1, GS_2, and GS_{3-5}. The exact days within each stage depends on crop varieties and other environmental factors such as 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 [29]. The output space of each membership function in the original model is a quantitative number between 0 and 1 that is referred to as optimality degrees, denoted by $Opt(X)$, where X: T, RH is the universe of universe of discourse (input). Plots of membership functions are adapted from [27] for demonstration in Fig. 1. An illustration is provided in plot labeled B of Fig. 1 for optimality of T at the vegetative to mature fruiting growth stage during sun hours. In this example, $T \in [24, 27]$ °C correspond to an optimal growth response equal to 1, ($Opt(T) = 1$). On the same plot, a wider reference border, i.e., $T \in [18.4, 32.2]$ °C, shown by red dotted lines, is associated with lower degree of optimal growth response, $Opt(T) \in [0.6, 1]$. In the other words, a greenhouse air temperature equal to 32.2 °C at sun hours is 60% optimal for tomato production in the 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 high quality fruit.

The marginal and ideal reference values of input spaces (T and RH, denoted by X), corresponding to optimality degree of 0 and 1, were precisely determined from graphical representations of the original model. These values are summarized in Table 1 and are results of experiments with tomato cultivar "Carusso" in an A-Shade greenhouse located at the Ohio Agriculture Research and Development Center with floor area of 7.3 m^2 [27,28]. 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 $Opt(X)_{GS,(Light)}$: $X \rightarrow [0, 1]$. In the other words, each T or RH readings in the greenhouse at time $t_{m,n}$, is associated to a value that quantifies its optimality for tomato production at specific stage and light condition. The two indexes m and n refer to specific minute and date of a measurement. Optimality degree as a concept is a quantitative value between 0 and 1 that represents how close an air temperature or relative humidity measurement is to the ideal requirement of tomato at specific growth stage. Mathematical descriptions of the membership functions defining optimality degrees of T and RH 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 $Opt(T)_{G1A}$, three functions, for sun, night and cloud conditions at the vegetative to mature fruiting growth stage (GS_{2-5}), denoted by $Opt(T)_{G2S}$, $Opt(T)_{G2N}$, and $Opt(T)_{G2C}$ respectively, and three functions for relative humidity for all light conditions at the early growth (GS_1), vegetative growth (GS_2) and flowering to mature fruiting growth stage (GS_{3-5}), respectively denoted by $Opt(RH)_{G1A}$, $Opt(RH)_{G2A}$, $Opt(RH)_{G3A}$.

2.2. Experiment setup

Data collection was carried out for a total of 147 days (from January, 5th, 2015 to May, 30th, 2015) in a Quanset-shape tropical greenhouse at the agricultural experimental field of the Putra University (3°00′34.4″N, 101°42′17.9″E), situated 20 km to the south of Kuala Lumpur, Malaysia. Elevation of the experiment site was 38.4 m above the mean sea level. The greenhouse had a frame structure made of 50 mm diameter galvanized iron pipes with west-east orientation, operating on natural ventilation. It was covered with anti-Thrips polyethylene monofilaments insect-proof net-screen film. Specification and properties of the cladding are as follow: round mesh type of 50-by-25 per 0.0254 m, hole size: 0.36 by 0.87 mm, thread diameter: 150 μm, weight: 0.06 kg/m^2, air flow resistance: 11.1, covering against light (shading factor): 0.36, transparent color with 3% ultraviolet absorbance. Greenhouse dimensions were: length (L) = 16 m, width (W) = 4.5 m, walls height (H) = 2.7 m, and Sagitta (S) = 0.8 m. Seeds of indeterminate F1 hybrid Truss tomato (Lycopersicon esculentum Mill) were sown

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