Modeling Air Temperature Inside an Organic Vegetable Greenhouse

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ABSTRACT

Air temperature is an important microclimate parameter in a greenhouse as it influences root growth and controls plant growth and development. Thus, the precise monitor and model temperature under greenhouse is needed to maintain the plants in optimal conditions. This research aims to model the temperature under a greenhouse using energy balance model. The study monitored the temperature inside and outside the greenhouse in a humid tropical environment. Based on the data, heat exchange constants of greenhouse components were derived, they were: 0.0029 (solar radiation), 0.8 (air) and 0.01 (heat exchange from greenhouse component). The calibrated model enables the calculation of temperature inside a greenhouse based on its outside air temperature, wind speed, and solar radiation. Testing the model against an independent time series showed the high accuracy of the model with an R2 value of 0.99, RMSE = 0.0085 and model efficiency Ef = 0.99. Based on the results, most advantageous strategies for air temperature control inside the greenhouse include the control of air ventilation.

INTRODUCTION

Planting media, climate, and plant parameters are the three main factors that control plant growth (Morakinyo, Kalani, Dahanayake, Ng, & Chow, 2017). Climate factors that greatly affect plant growth are solar radiation, air temperature, wind speed, and rainfall (Hatfield & Prueger, 2015). Indonesia has a humid tropical climate with humidity of about 80% and air temperature that reaches up to 35°C. Such conditions can severely affect plant growth (William, Suharto, & Tanudjaja, 2016). Thus, a greenhouse or a green house becomes one of the solutions to control the climate (Mutui, Sesabo, Ishengoma, & Opile, 2012).

The microclimate inside the greenhouse might be different from the outside or field. The microclimate is defined as the set of climatic factors that have a direct physical effect on an environment (Wong, Lai, Low, Chen, & Hart, 2016). The microclimate is influenced by several factors such as wind speed, humidity, irrigation, etc. (Ebrahimabadi, Nilsson, & Johansson, 2015). Air temperature is an important microclimate parameter under the greenhouse that can impact on the root growth and controls how fast or slow a plant develops (Runkle, 2006). Besides that, the air temperature is also significant parameter to calculate water consumption through evapotranspiration (Muharomah, Setiawan, Purwanto, & Liyantono, 2020). Thus, it is important to be able to predict the air temperature inside the greenhouse to maintain optimal temperature condition based on the plants need.

Several studies have proposed models to predict the temperature inside the greenhouse using empirical data such as time series analysis, the artificial neural network or mechanistic models as shown in Table 1. Those researches were conducted in the semi-tropical regions which have four seasons. Furthermore, the greenhouse used in this study has unique characteristics that are different from the published reports. Those published
results cannot be applied in the humid tropical region such as in Indonesia (Sethi, Sumathy, Lee, & Pal, 2013). However, models based on mass and energy balance are universal and thus can be adapted and calibrated for greenhouses in Indonesia.

This research aims to derive a predictive equation for the temperature inside a greenhouse in Indonesia by applying an energy balance method.

**MATERIALS AND METHODS**

The research was conducted at the organic vegetable greenhouse with natural ventilation, located at the Department of Civil and Environmental Engineering, IPB University from 5 February to 26 June 2018.

**Greenhouse Description**

The size of the greenhouse was 9 x 3 m (27 m²). The orientation of the greenhouse was the east-west direction. The greenhouse was covered with a polycarbonate roof and a net wall (Fig. 1). The crops used was (Brassica oleracea var. alboflagbra) with organic fertilization. Vegetable seedlings were grown for about 14 days outside the greenhouse and then transplanted under the greenhouse in a soil media for 40 days.

The measurement of solar radiation was carried out using the Decagon PYR Pyranometer sensor while the air temperature was measured using using Decagon VP-4 (Temperature, Humidity and Pressure Sensor) sensor. The data were collected every 15 minutes during the three periods of study (3 times cultivation for 140 days).

**Model Development**

Air temperature inside the greenhouse was influenced by environmental factors, such as solar radiation, wind speed, and outside air temperature. The energy balance of a greenhouse can be written as Equation 1 (Boulard & Wang, 2000), and the heat transfer equation can be defined by Equation 2 (Lienhard IV & Lienhard V, 2008).

\[
Q_{\text{sol}} = Q_{\text{con}} + Q_{\text{vent}} + Q_{\text{evp}} + Q_{\text{sto}} \quad \text{1)}
\]

\[
\frac{dQ}{dt} = m c \frac{dT}{dt} \quad \text{2)}
\]

where:
- \(Q\) is heat transfer rate (W),
- \(\frac{dQ}{dt}\) is rate of change internal thermal energy,
- \(m\) is mass,
- \(c\) is specific heat coefficient,
- \(Q_{\text{sol}}\) is the energy balance equation consists of solar radiation,
- \(Q_{\text{con}}\) is heat transfer from the surface,
- \(Q_{\text{vent}}\) is heat loss by infiltration and ventilation,
- \(Q_{\text{evp}}\) is heat by transpiration, and
- \(Q_{\text{sto}}\) is heat storage in the greenhouse.

**Table 1. Past study about air temperature modeling inside a greenhouse**

| Researcher | Location | Type of Greenhouse | Crop | Method |
|------------|----------|--------------------|------|--------|
| Frausto, Pieters, & Deltour, 2003 | Western European | Unheated and naturally ventilated | - | Auto regressive model |
| Kittas, Bartzanas, & Jaffrin, 2003 | The Mediterranean | Shaded greenhouse with evaporative cooling | - | Simple climate model |
| Lekouch, El Jazouli, Wifaya, & Bouirden, 2011 | South region of Morocco | Naturally ventilated in plastic greenhouse | Tomato | Energy balance |
| Ma et al., 2019 | China | Closed with cooling system | - | Heat transfer equation |
| Reyes-Rosas, Molina-Aiz, Valera, López, & Khamkure, 2017 | The Mediterranean | Naturally ventilated with a polypropylene mulch covering | Tomato | Energy balance |
| Arslan & Dölek, 2019 | Turkey | Heated greenhouse with coal | - | Energy and mass balances |
| Singh, Singh, & Singh, 2018 | Hot and semi arid (India) | Naturally ventilated in plastic greenhouse | Cucumber | Heat or mass transport processes |
| Zhao, Teitel, & Barak, 2001 | Israel | Closed and naturally ventilated, commercial greenhouse | Tomato | Ventilation rate equation |
Based on the heat transfer theory, a greenhouse can be defined as a system of heat from solar radiation, heat in the air, and heat absorbed by components of the greenhouse. In mathematical terms, they were formulated into Equation 3.

\[
\tau R (1 - \varepsilon) - \frac{\rho C_p G}{S_g} (T_{in} - T_{out}) - \frac{S_c h}{S_g} (T_{in} - T_{out}) = 0 \quad 3 \]

where:
\( \tau \) is coefficient of transmissivity,
\( R \) is solar radiation outside greenhouse (W/m²),
\( \varepsilon \) is coefficient of evaporation,
\( \rho \) is density of air (kg/m³),
\( C_p \) is specific heat of air (W s/kg K),
\( G \) is ventilation rate (m³/s),
\( S_g \) is area of the ground (m²),
\( S_c \) is area of the cover (m²),
\( T_{in} \) = inside air temperature (K),
\( T_{out} \) = outside temperature (K), and
\( h \) is overall heat exchange coefficient (W/m² K).

Overall, the heat exchange coefficient is a function of wind speed given from Equation 4, and the ventilation rate is a function by the wind speed and ventilation rate, given from Equation 5.

\[
h = a + b U_v \quad \text{4)}
\]

\[
G = \frac{W U_v + \rho_C G}{S_g} \quad \text{5)}
\]

Mesmoudi, Soudani, & Bournet (2010) simplified Equation 6 to Equation 7.

\[
T_{in} = T_{out} + \frac{\tau R (1 - \varepsilon)}{a S_g + b S_g U_v + \rho_C G} \quad \text{6)}
\]

\[
T_{in} = T_{out} + \frac{\tau R a}{\gamma + \beta U_v} \quad \text{7)}
\]

where:
\( a, b, W = \text{constant}, \)
\( U_v = \text{wind speed in outside greenhouse (m/s)} \)
\( \nu_0 = \text{ventilation rate not include the wind (m}^3/\text{s)} \)

Equation 3 is further rearranged into Equation 6:

\[
\text{Model Calibration and Validation}
\]

Outlier data were first separated before analysis. Outliers are defined as data that have different statistical properties and characteristics of the general data and have relatively few incidence events (Iqbal, Habib, Khan, & Kashif, 2020). Outlier data were calculated by outlier equation (Chow, Maidment, & Mays, 1988).

Statistical criteria were calculated to calibrate the quality of the model, and these includes the
coefficient of determination ($R^2$), root mean square error (RMSE) and model efficiency (Ef) (Tribouillois et al., 2018). Equation 8 and 9 show the RMSE and model efficiency formula. The accuracy of the model was evaluated by comparing the predicted and measured data.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2} \quad \text{........................................ 8)$$

$$Ef = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \sigma)^2} \quad \text{........................................ 9)$$

where:

- $n$ = number of data,
- $P_i$ = predicted values,
- $O_i$ = observed values and
- $\sigma$ = mean of observed values.

**RESULTS AND DISCUSSION**

The air temperature inside the greenhouse was higher compared to the outside (Fig. 3). The air temperature distribution within the greenhouse and open space during the study period are shown as in Fig. 2 and Table 2. The average daily temperature requirement for kailan vegetable growth is 25-35°C. At low temperatures, the plants will show degenerative symptoms, like the death of leaf tissue, and eventually the plants die. At high temperatures, the plants will die because the evaporation process is too large.

According to observations, the temperature range under the greenhouse was not in accordance with the temperature range needed by kailan for optimal growth, the maximum and minimum temperature inside the greenhouse exceed from the daily requirement of the tested plant. To control the temperature inside the greenhouse, therefore, the components that contributed to the largest heat inside the greenhouse were examined properly.

Based on the air temperature data, the highest air temperature occurred on 16 April 2018 (outside) and 25 March 2018 (inside). The minimum air temperature occurred on 18 March 2018 on both inside and outside of greenhouse.

**Table 2. Statistics of air temperature data**

| Data               | Max   | Median | Min   | Mean  | Std. Dev |
|--------------------|-------|--------|-------|-------|----------|
| Air Temperature Outside (Tout) | 39.00 | 25.40  | 20.70 | 26.73 | 3.56     |
| Air Temperature Inside (Tin)      | 39.80 | 25.80  | 21.00 | 27.20 | 3.74     |

**Fig. 2. Air temperature distribution inside the greenhouse during observation period**
Fig. 3. Air temperature in the inside and outside greenhouse (25 March 2018)

Fig. 4. Coefficient of transmissivity
The coefficient of transmissivity was estimated from 7452 solar radiation data. Data were analyzed using linear regression to understand the relationship between radiation inside and outside the greenhouse. Radiation in outside and inside greenhouse during study has a linear relationship with an estimated coefficient of transmissivity of 0.455 and $R^2 = 0.88$ (Fig. 4).

Daily transmissivity was changed every day and influenced by the amount of sunlight and the roof conditions. The decrease on transmissivity can be caused by dirty roof due to dust or other materials. These increment of transmissivity occurred when the roof transparency increased when the dirt was wiped out during by rainfall.

**Heat Constants of Greenhouse Components**

At least three constants that are related with the energy balance equation in the greenhouse. $\alpha$ represents the function of solar radiation, $\beta$ for heat exchange, and $\gamma$ for air component from greenhouse components. $\alpha$, $\beta$ and $\gamma$ were obtained from an optimization of Equation 6 based on measured data using the Solver function on Microsoft Excel. The data of $T_{in}$, $T_{out}$, $\tau$, $R$ and $U_e$ were obtained from primary and secondary field observations. There are 13374 data from 5 months measurements that were used to this analysis and the results are presented in Table 3.

**Table 3. Constants representing greenhouse components calibrated from observations.**

| Constants | Value   |
|-----------|---------|
| $\alpha$  | 0.0029  |
| $\gamma$  | 0.8000  |
| $\beta$   | 0.0100  |

The model with optimised parameters has $R^2 = 0.98$ (Fig. 5) and RMSE = 0.0050. The result was better than the findings of Mesmoudi, Soudani, & Bourret (2010) that has an RMSE value of 0.0668. From $\alpha$, $\beta$ and $\gamma$, other components, i.e. $\epsilon$ (coefficient of evaporation), $a$, $b$, $w$ (constants of ventilation rate) and $\nu_o$ (ventilation rate not include the wind) were also derived using the Solver optimizer, as shown in Table 4.

Table 4 and Table 5 show the results of data analysis by month and commutative for the whole period (5 months). The results indicated analysing data for the whole period has better accuracy than analysing the data month-by-month.
Sethi, Sumathy, Lee, & Pal (2013) stated that the coefficients in each greenhouse are different because the value depends on the in situ environmental conditions. Different heat transfer coefficients were also reported by several studies (e.g., Abdel-Ghany & Kozai, 2006; Fernández & Bailey, 1992; Feuilloley & Issanchou, 1996; Nijskens, Deltour, Coutisse, & Nisen, 1984).

**Modeling Air Temperature Inside the greenhouse**

The analysis using 5 month data gave the lowest RMSE with high $R^2$ (Table 4). Thus, equation 10 can be used to predict air temperature inside the greenhouse.

$$T_{in} = T_{out} + \frac{0.0029T_R}{0.8 + 0.01U_w} \hspace{1cm} \text{(10)}$$

Furthermore, this calibrated equation allows a comparison of the values between the predicted and measured temperature inside the greenhouse.

**Validation**

Air temperature inside greenhouse was built using five months data. In this validation step, the air temperatures inside the greenhouse during October 2018 can be predicted. A comparison of the predicted with the observed temperature inside the greenhouse showed that the model has an excellent fit with RMSE = 0.0085 and $R^2 = 0.98$ as presented in Fig. 6. The model can predict the temperature condition inside a greenhouse as viewed in Table 6 and Fig. 7.

| Table 4. Constants value based on data analysis by month and all data |
|-----------------------------------------------|
| **Time - Parameter** | **A** | **γ** | **β** | **ε** | **a** | **b** | **ν₀** | **w** |
|----------------------|------|------|------|------|------|------|--------|------|
| February             | 0.0049 | 0.8136 | 0.0112 | 0.9951 | 0.3565 | 0.0030 | 0.0123 | 0.0002 |
| March                | 0.0038 | 0.8016 | 0.0131 | 0.9962 | 0.3565 | 0.0030 | 0.0124 | 0.0002 |
| April                | 0.0036 | 0.8001 | 0.0122 | 0.9964 | 0.0198 | 0.0030 | 0.0173 | 0.0002 |
| May                  | 0.0001 | 0.8179 | 0.0220 | 0.9999 | 0.0198 | 0.0030 | 0.0177 | 0.0004 |
| June                 | 0.0008 | 0.8329 | 0.0201 | 0.9992 | 0.0198 | 0.0030 | 0.0180 | 0.0004 |
| 5-month              | 0.0029 | 0.8000 | 0.0100 | 0.9971 | 0.1202 | 0.0030 | 0.0158 | 0.0002 |

| Table 5. RMSE and $R^2$ based on analysis by month and all data |
|-----------------------------------------------|
| **Time Parameter** | **RMSE** | **$R^2$** |
|---------------------|---------|---------|
| February            | 0.0096  | 0.98    |
| March               | 0.0106  | 0.98    |
| April               | 0.0126  | 0.98    |
| May                 | 0.0098  | 0.98    |
| June                | 0.0102  | 0.98    |
| 5-month             | 0.0050  | 0.98    |

| Table 6. Value of statistical criteria |
|----------------------------------------|
| **Parameter** | **Criteria** | **Value** |
|---------------|--------------|-----------|
| $R^2$         | 0 - 1        | 0.98      |
| $RMSE$        | 0 - ~        | 0.0085    |
| $Ef$          | ~ - 1        | 0.99      |

**Air Temperature Control Strategy inside a Greenhouse**

Based on equation 10, the air temperature inside greenhouse was affected by air temperature, solar radiation and wind speed from outside of the greenhouse. Solar radiation is difficult to control, and the best way to control temperature is using ventilation. Equation 7 shows that if the solar radiation component is higher than the wind speed, the air temperature inside the greenhouse will increase.

Hassanien, Li, & Lin (2016) divided temperature control strategy in greenhouse into the heating, cooling, lighting, and CO₂ enrichment systems. Ganguly & Ghosh (2011) reported that cooling technology was used to reduce the air temperature, such as a fan pan evaporative cooling that can reduce the temperature down to 4-5°C. A sensor network was also used to monitoring the environmental condition inside greenhouse and the sensor was connected to a temperature controlling device (Prabhu, 2016), though the methods as considered costly for small-scale greenhouse.
Fig. 6. Correlation of the predicted and observed values of air temperature inside the greenhouse

Fig. 7. Predicted and observed air temperature inside the greenhouse (Day 1 and Day 31)
Natural ventilation could be an option in which the air inside the greenhouse will be replaced by cooler air temperature from outside (Rodríguez, Berenguel, Guzman, & Ramírez-Arias, 2015). Kacira et al. (2008) reported additional natural ventilation in each side of a greenhouse can significantly reduce inside air temperature. Natural ventilation does not work well if outside wind velocity is low. Thus, the combination of natural ventilation with another methods like shading system can be an alternative way out in reducing air temperature inside the greenhouse during such conditions (Both, 2008). Roof shade can be adjusted depending on the solar radiation conditions in greenhouse (Sethi, Sumathy, Lee, & Pal, 2013).

CONCLUSION

The sources of heat component inside the greenhouse were solar radiation, outside air temperature and heat exchange from greenhouse component. The constants values of these components were calculated as 0.0029 from solar radiation, 0.8 from outside air temperature and 0.01 from the heat exchange from greenhouse components. Air temperature inside greenhouse could be calculated using $T_{in} = T_{out} + \frac{0.0029A_{s}}{R_{n}}$ based on environmental data in outside greenhouse. The accuracy of the model to predict inside temperature in greenhouse was considered high with $R^2$ value of 0.99, RMSE = 0.0085 and Ef = 0.99.

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