Construction of a Cultivation Simulator Considering Heat Insulation Film Characteristics and Fruit Cracking in the Asian Monsoon Region

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Abstract

This study aimed to construct a cultivation simulator of high-quality tomato cultivation in hot and humid areas. In particular, the heat-shielding film characteristics and fruit cracking specific to high temperatures and humidity were modeled. The results of yield simulations based on meteorological data were compared with the results of cultivation test. As a result, these were almost in agreement with the cultivation results, suggesting the effectiveness of the simulation considering the characteristics of the film and the fruit cracking rate.

[Keywords] cultivation simulator, heat insulation film, fruit cracking, high-temperature, humidity

I Introduction

Recently, there has been increasing interest in safe, high-quality Japanese food due to population increases and the economic upliftment of Asia (Nakano, 2016). Greenhouses are becoming dangerously hot in summer in Japan. Therefore, it is necessary to establish tomato cultivation techniques for Japanese horticulture compatible with high temperatures and intense sunlight. At high temperatures, the yield of tomato fruits decreases due to physiological disorders, such as reduced plant vitality and fruit cracking (Suzuki, 2019). Various methods, such as ventilation, heat pumps, and cooling, have been used to counter greenhouse cultivation temperatures (Kawashima et al., 2011; Hiei et al., 2015). However, when temperatures are high outside, sufficient cooling effects are not obtainable through ventilation. Similarly, cooling with mist is not expected to be sufficiently effective because of restricted water evaporation at high humidity. The use of shielding material should reduce the rise in temperature due to heat from sunlight, as it decreases the heat energy that enters the house from sunlight (Wada et al., 2013). However, it is possible that blocking sunlight will reduce the light required for plant growth, resulting in poor plant growth (Hamamoto et al., 2000).

Therefore, a demonstration project of high-quality tomato cultivation based on the Asian monsoon region was examined. The authors investigated the effect of the insulating film on tomato growth in subtropical greenhouses under a low-node pinch and high-density planting system. The plants were cultivated in two greenhouses: one covered with a heat insulating film and the other covered with polyolefin (PO) film. Additionally, we examined the construction of a cultivation simulator for predicting the yield of high-quality tomato cultivation in the hot and humid regions of Asia. In particular, a simulator was constructed considering the characteristics’ effects of heat shield film on the cultivation environment in a greenhouse. The fruit cracking rate specific to hot and humid areas was also modeled. The simulation by the constructed model was compared with the cultivation test results to verify the model’s effectiveness. This study provides a reference for using this model, which incorporates environmental parameters to determine and improve the yield of tomatoes in greenhouses in hot and humid regions of Asia.

II Construction of a Yield Prediction Simulator Considering Film Characteristics and the Fruit Cracking Rate

The yield prediction simulator was constructed by combining an environmental model considering the influence of the heat insulating film, a cultivation model, and a model considering the rate of fruit cracking.

1. Environmental model

The environmental model was constructed by adding the influence of optical characteristics to the conventional heat balance model for deriving the house temperature. A basic heat balance model has already been incorporated in the greenhouse for tomato cultivation in the Asian monsoon region (Matsuo et al., 2019a). In this model, the greenhouse was divided into a large number of cells and the temperature of the air in each cell was calculated (Fig. 1). In addition, each

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The temperature change in unit time for each cell was calculated by heat conduction and heat from external sources as shown in Eq. (1).

$$\frac{\rho_i C_i V_i}{d_t} \frac{d T(t)}{d t} = \lambda_i \left( \frac{\partial^2 T_i(t)}{\partial x^2} + \frac{\partial^2 T_i(t)}{\partial x^2} \right) + q_i(t) \quad (1)$$

Where, $\rho_i$ (kg m$^{-3}$) is the density, $C_i$ (J°C$^{-1}$ kg$^{-1}$) is the specific heat, $V_i$ (m$^3$) is the product, and $\lambda_i$ (J s$^{-1}$ m$^{-1}$ °C$^{-1}$) is the thermal conductivity in each medium. The heat from external sources entering each cell of $q_i$ (J) includes heat derived from sunlight, convection heat, radiation heat, and heat from plant transpiration.

As shown in Eq. (1), four indexes were used for the analysis of the optical characteristics. The visible light transmittance $\omega_f$ that affects photosynthesis, infrared transmittance $\omega_a$ that affects the temperature inside the greenhouse, and absorption rate $\alpha_f$ that affects the film temperature. By modifying these variables according to the weather conditions, analyzing the characteristics of the heat insulation film becomes possible.

As shown in Fig. 2, four indexes were used for the analysis of the optical characteristics. The visible light transmittance $\omega_f$ that affects photosynthesis, infrared transmittance $\omega_a$ that affects the temperature inside the greenhouse, and absorption rate $\alpha_f$ that affects the film temperature. By modifying these variables according to the weather conditions, analyzing the characteristics of the heat insulation film becomes possible.
by temperature.

In addition, the model classified the tomato fruit position into three vertical directions based on actual cultivation. Each yield was obtained from the growth state in each stage, and the total yield was obtained from the sum of them.

The amount of solar radiation that arrives as much as the group drop part is reduced. Therefore, the percentage of solar radiation reaching tomatoes in each stage was calculated as 33% (1st), 66% (2nd), and 100% (3rd). The fruit temperature and the rate of fruit cracking were calculated for each stage, considering that the amount of solar radiation differs for each stage.

3. Fruit cracking model

Another important aspect of the modeling was fruit-splitting properties, which are characteristic of hot and humid areas. Fruit cracking of tomatoes occurs due to a complex combination of factors, such as strong sunlight, the amount of watering, and the pattern of fruit enlargement. Shading and water management are considered countermeasures for these conditions. We constructed a model organized by the fruit cracking rate and fruit temperature relationship to predict this fruit cracking rate.

The heat balance model of the fruit was expressed using solar radiation, radiation, and convection as shown in the following formula, which was based on the Nakagawa model (1958).

\[
Vq\rho C_t \frac{dT_f(t)}{dt} = q_L(t) + q_R(t) + q_T(t)
\]  
(5)

\[
q_L(t) = \pi r^2 L \cdot \alpha_f \cdot \varepsilon \cdot (T_f(t) - T_v(t))
\]  
(6)

\[
q_R(t) = 4\pi r^2 \cdot \varepsilon \cdot (T_f(t) - T_v(t))
\]  
(7)

\[
q_T(t) = 4\pi r^2 \cdot h \cdot (T_f(t) - T_v(t))
\]  
(8)

\[
h = \frac{\lambda}{2r} \cdot 0.33 \left(\frac{2r \cdot u}{v}\right)^{0.6}
\]  
(9)

Where, \(V_t\) (m\(^3\)) is the volume of tomato, \(\rho_t\) (kg m\(^{-3}\)) is the density of tomato fruit, and \(C_t\) (J°C\(^{-1}\) kg\(^{-1}\)) is the specific heat of tomato fruit. \(q_L\) (J s\(^{-1}\)) represents the amount of heat incident on the fruit by solar radiation, \(q_R\) (J s\(^{-1}\)) represents the radiant heat on the fruit, and \(q_T\) (J s\(^{-1}\)) represents the amount of heat lost in the flow by the fruit. \(T_f\) (°C) is the surface temperature of tomato and \(T_v\) (°C) is the temperature of the cultivation environment, which are calculated from these heat balance models. \(r\) (m) is the radius of tomato, \(Sun\) (J s\(^{-1}\) m\(^{-2}\)) is the amount of solar radiation per unit area, and \(\alpha_f\) (-) is the absorption rate of sunlight in the tomato epidermis. \(\varepsilon\) (-) represents the emissivity on the surface of tomato. \(h\) (J s\(^{-1}\) m\(^{-2}\) °C\(^{-1}\)) is the convective heat transfer coefficient of the tomato surface and is defined by Eq. (9), \(\lambda\) (J s\(^{-1}\) m\(^{-1}\) °C\(^{-1}\)) is the thermal conductivity of air, \(u\) (m s\(^{-1}\)) is the wind velocity, and \(v\) (m\(^3\) s\(^{-1}\)) is the kinematic viscosity coefficient of air.

The fruit cracking rate was estimated by determining the relationship between the fruit temperature calculated using the formula and fruit cracking rate in the cultivation test.

4. Combined simulator

Finally, a concatenated simulator was constructed by combining an environmental model that takes into account the effects of the thermal insulating film, a cultivation model, and a fruit cracking model (Fig. 4). In this simulator, the yield is calculated from the relationship between the reached integrated temperature and the integrated photosynthesis amount obtained by the simulator. The final fruit yield was determined by multiplying the cumulative photosynthesis amount by the fruit cracking rate.

III Cultivation Test and Cultivation Simulation

1. Cultivation tests

Cultivation tests were conducted in a greenhouse at the International Agricultural Research Center on Ishigaki island and at the National Agriculture and Food Research Organization in Tsukuba in the summer. The climate of Ishigaki island is classified as subtropical, with high insolation in summer and high temperature and humidity throughout the year. Details of the cultivation tests are reported by Nakayama et al. (2021). The main cultivation conditions are as follows. The greenhouses were 6 m wide and 25 m long, and the roof height was 3.3 m. Tomatoes were cultivated in two greenhouses facing north-south: one (A) covered with PO film (Distaer, Mitsubishi Chemical Agri Dream Co. Ltd., Japan) and the other (B) with heat insulating film (MF-250, FUJIFILM Corp., Japan). A shade curtain of 65% transmitted light is installed under the center of the ceiling of the PO film greenhouse (A). The characteristic values of the film are shown in Fig. 5. Near
infrared rays are blocked by 60% in the B film. This shade curtain was set to close at 31°C or higher on Ishigaki island and 35°C in Tsukuba. The daily solar radiation was calculated from the shading rate, which was used to calculate the yield. A mist cooling system, heat pumps, ventilation fans, circulation fans, and roll-up ventilation windows were also set up in each greenhouse. The ventilation fan was activated when the temperature in the greenhouse exceeded 29°C on Ishigaki island and 35°C in Tsukuba in the morning at both locations. The mist cooling system was operated at 30°C or higher inside the greenhouses. Night cooling and CO2 fertilization were also performed.

2. Cultivation simulation

The simulations were analyzed based on cultivation data conducted in spring and summer (June-September), taking into account the Asian monsoon region. Table 1 shows the simulation conditions and the parameters used. In the simulations, the heat sources of the insulating and PO films and the changes in yield due to the different films were analyzed in the Ishigaki and Tsukuba fields, respectively.

IV Simulation Results and Discussion

1. Simulation results for film effects

(1) Temperature in the greenhouse

Figures 6 and 7 show the results of investigating the source of heat in the heat insulation film (B) and PO film (A). Here, the heat from sunlight, the upper film, the pipe, and a sheet...
covered on the ground were calculated by simulation. This shows that the total amount of heat in the greenhouse is not significantly different between the two, but the main factors of heat show that they are different between films. It can be seen that the heat from sunlight is the main drive source for the PO film (A), and the heat from the upper film is the main drive source for the heat insulation film (B). Therefore, it was considered that heat is reduced from the film such as sprinkling water instead of from the ground in the greenhouse (B) of the heat insulation film, and ventilation is important to reduce the heat in the greenhouse (A) of the PO film.

(2) Fruit temperature

Figure 8 shows the estimated results of the fruit temperature of each stage in the greenhouse for each film area. The fruit temperature was particularly high in the PO film (A), indicating that the fruit temperature was substantially affected by radiation. Therefore, heat insulation film (B) could be effective for reducing transmission in the near-infrared region.

In the cultivation test, sufficient irrigation control was performed at the time of harvesting, and the fruits were strongly affected by solar radiation due to summer cultivation. Therefore, in this analysis, the fruit cracking rate was estimated from the relationship of fruit temperature. Figure 9 shows the relationship between the fruit temperature obtained by simulation and the fruit cracking rate obtained from the tomato cultivation test. Although there are variations such that the coefficient of determination is 0.8, it is considered that there is a general correlation. From this result, a relation of Eq. (10) was derived, and this relation was used to estimate the final yield shown in the next chapter.

\[
\text{r}_{\text{crack}} = \max \left[ 0, \min (0.19 \cdot T_f - 5.47, 1) \right]
\]

### 2. Comparison of yield prediction and actual measurement

The final yield predicted using the constructed simulator was compared with the cultivation test results. Table 2 shows the main cultivation tests and simulation results.

Figure 10 shows the relationship between the reached integrated temperature and the integrated photosynthesis amount obtained by simulation. The integrated photosynthesis amount corresponding to the reached integrated temperature is the final estimated yield.

Figure 11 and 12 show a comparison between the yield results (Field 1–4) in the cultivation test of Ishigaki island and Tsukuba and the yield prediction results (Calc. 1–4) by simulation. The yield of Calc. 1–4 was estimated using the constructed simulator and the relational expression of fruit cracking rate under the meteorological conditions of the cultivation test area. In addition, the distribution rate of photosynthetic products, which is an important parameter, was set to be constant for each film from the analysis results of the cultivation test results in Table 2.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Tsukuba</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drymater weight</td>
<td>151.3</td>
<td>128.5</td>
<td></td>
</tr>
<tr>
<td>Number of flowers</td>
<td>5.95</td>
<td>5.97</td>
<td></td>
</tr>
<tr>
<td>Fruit rate (%)</td>
<td>82.0</td>
<td>77.5</td>
<td></td>
</tr>
<tr>
<td>Distribution rate</td>
<td>29.9</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>Field data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tsukuba A</td>
<td>Filed 1</td>
<td>6.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Calc. 1</td>
<td></td>
<td>6.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Calc. 2</td>
<td>Field 2</td>
<td>6.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Calc. 3</td>
<td>Field 3</td>
<td>6.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Calc. 4</td>
<td>Field 4</td>
<td>7.8</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Coefficient of determination (field data and simulation) yield is $R^2 = 0.98$ and cracking is $R^2 = 0.96$. 

**Table 2** Main cultivation and simulation results

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**Fig. 8** The simulated fruit temperature of each stage

**Fig. 9** The relationship between the fruit temperature obtained by simulation and the fruit cracking rate obtained from the tomato cultivation test
Here, the amount actually harvested per plant and the final yield considering fruit cracking are shown for each film difference. The findings show that the yield differs depending on the film. According to this, in Tsukuba (June), the yield in PO (A) was slightly higher than that in the heat insulating film (B) because the temperature inside the house and the amount of solar radiation were high. However, due to the high cracking rate of the fruit, the final commercialized yield was higher for the heat shield film (B). This suggests the effectiveness of the heat shield film in hot and humid areas.

The simulation results were in good agreement with the actual yield, demonstrating the effectiveness of the constructed simulator and fruit cracking rate model. In order to investigate the accuracy of the simulation, we found the variation between the measured and predicted values of yield and fruit cracking rate. Table 2 shows these results. Although there is a good correlation in both cases, it can be seen that the fluctuation range of the estimated fruit crack rate is larger than that of the yield. It was suggested that accurate estimation of the fruit cracking rate will be important when the simulator is actually applied in the future.

V Conclusions

The purpose of this study was to construct a simulator that considers the characteristics of heat insulation films for high-quality tomato cultivation in hot and humid regions of Asia. We constructed a composite model that combines an environmental model of the greenhouse and a tomato growth model. Additionally, the rate of fruit cracking specific to hot and humid areas was included in the model. The simulation results agree with the actual yield. Therefore, we suggest this simulation model, which incorporates meteorological data, integrated temperature, integrated photosynthesis, and the fruit cracking rate, effectively predicts tomato yield and could improve tomato yields in hot and humid regions of Asia.

Acknowledgements

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Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_v, T_f$</td>
<td>°C</td>
<td>Temperature of greenhouse air and tomato fruit</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\rho_c, \rho_T$</td>
<td>kg m$^{-3}$</td>
<td>Density of greenhouse air and tomato fruit</td>
</tr>
<tr>
<td>$C_v, C_T$</td>
<td>J kg$^{-1}$°C$^{-1}$</td>
<td>Specific heat of greenhouse air and tomato fruit</td>
</tr>
<tr>
<td>$V_v, V_T$</td>
<td>m$^3$</td>
<td>Volume of greenhouse air and tomato fruit</td>
</tr>
<tr>
<td>$S_m, S_i$</td>
<td>nmol</td>
<td>The amount of photosynthesis stored in the source and sink</td>
</tr>
<tr>
<td>$F_L$</td>
<td>m$^2$</td>
<td>The leaf area</td>
</tr>
<tr>
<td>$i_t$</td>
<td>nmol m$^{-2}$ s$^{-1}$</td>
<td>The translocation rate</td>
</tr>
<tr>
<td>$p$</td>
<td>nmol m$^{-2}$ s$^{-1}$</td>
<td>Photosynthesis rate</td>
</tr>
<tr>
<td>$g$</td>
<td>nmol s$^{-1}$</td>
<td>The rate of movement to the organ</td>
</tr>
<tr>
<td>$L_t$</td>
<td>s</td>
<td>The time delay in the translocation</td>
</tr>
<tr>
<td>$D_L, D_R$</td>
<td>--</td>
<td>Distribution coefficients of leaf, stem and flower</td>
</tr>
<tr>
<td>$m_L, m_s$</td>
<td>nmol</td>
<td>Weight of leaf, stem and flower</td>
</tr>
<tr>
<td>$m_f$</td>
<td>--</td>
<td>The rate of movement to the fruit</td>
</tr>
<tr>
<td>$q_L, q_R, q_T$</td>
<td>J s$^{-1}$</td>
<td>The amount of heat incident on the fruit by solar radiation, radiation and convection to the fruit</td>
</tr>
<tr>
<td>$r$</td>
<td>m</td>
<td>The radius of tomato</td>
</tr>
<tr>
<td>$Sun$</td>
<td>J s$^{-1}$ m$^{-2}$</td>
<td>The amount of solar radiation per unit area</td>
</tr>
<tr>
<td>$\alpha_f$</td>
<td>--</td>
<td>The absorption rate of sunlight in the tomato fruit</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>--</td>
<td>The emissivity on tomato fruit</td>
</tr>
<tr>
<td>$h$</td>
<td>J s$^{-1}$ m$^{-2}$°C$^{-1}$</td>
<td>The convective heat transfer coefficient of the tomato</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>J s$^{-1}$ m$^{-1}$°C$^{-1}$</td>
<td>The thermal conductivity of air</td>
</tr>
<tr>
<td>$u$</td>
<td>m s$^{-1}$</td>
<td>The wind velocity</td>
</tr>
<tr>
<td>$v$</td>
<td>m$^2$ s$^{-1}$</td>
<td>The kinematic viscosity coefficient of air</td>
</tr>
</tbody>
</table>

References


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