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Effects of integrated environmental factors and modelling the growth and development of tomato in greenhouse cultivation

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Abstract. Effects of environmental factors on the growth and development of tomato plants in greenhouse cultivation were investigated. Tomato (*Lycopersicon esculentum* Mill. cultivar "Momotaro") was cultivated by solution culture system using solid medium from November 2017 to May 2018 in the glass greenhouse with 66.43 m^2 of floor area. Environmental factors including temperature, humidity, light intensity and CO_2 concentration in the greenhouse were recorded every 10-minute during cultivation. Mathematical models were developed to fit the data to determine the relationship between environmental factors and the growing parameters of tomato plants. It was observed that the percentage of flowers translated into fruits and clusters tended to decrease in upper clusters on tomato plants. Fruit yield was estimated at about 31 kg/m^2 and 5.56 kg/plant, and fruit weight varied among plants from 3.73 kg to 7.34 kg. Mathematical modelling using measured indices represented moderate significant relationships between start ripening date (SRD), harvesting date (HD), and cumulative heat unit (CHU), and cumulative light intensity (CLI) as $R^2 = 0.67$, between cluster occurrence and CHU as $R^2 = 0.69$.

Keywords: Tomato; Mathematical modeling; Cumulative heat unit; Cumulative light intensity; Start ripening date

1. Introduction

One of the important trends in greenhouse cultivation involves mathematical modeling, which can provide a description of changes in plant growth caused by environmental conditions, such as temperature, humidity, light intensity, CO_2 concentration, and other factors, i.e., water, fertilizer, and air movement [1]. This approach will also contribute to making ideal cultivation systems that are logistically controlled in introducing ideal plant growing potential [2].

In several kinds of environmental factors, the temperature is obviously important to the growth and development of tomato from planting to maturity. Especially the concept of cumulative heat unit (CHU) was often used. CHU was as the amount of warmth accumulated to plant during its growth. This index was calculated based on periodical measured temperature to integrate these among 24 hours, which is applied to predict plant development information, for example, the elongation rate of stems, the coming and blooming date of clusters and flowers, the maturation and ripening time of fruits. In addition, CHU was usually applied to assess the suitability of a region for production of a particular crop; estimate the growth-stages of crops, weeds or even life stages of insects; predict best timing of fertilizer or pesticide application; estimate the heat stress on crops; plan spacing of planting dates to produce separate harvest dates. Growing periods of a tomato fruit are simply divided into

flower bloomed, fruit cell division and enlargement, maturation, and ripening. These were fully controlled by environmental factors. Therefore, estimated days flower bloom (FBD) and fruit start ripening (SRD), fruit size and color in a relationship with temperature are essentially important for farmers because these can be used to estimate the yield and harvesting time correctly.

The light intensity (LI) is also a crucial factor in the growth of any crops. Cumulative light intensity (CLI), the index was calculated by summing of LI incoming in greenhouse obtained during the specified period during cultivation. It measures the number of photosynthetically active photons (photons in the PAR range) accumulated in a square meter. CLI strongly affected photosynthesis and respiration through leaves and positively related to the productivity of tomato fruit. CLI also resulted in changes the timing of flowering [3].

The aim of this study was to contribute the development of decision support system on greenhouse tomato production, which can support operators to set more precise controlling of plant growth by operating composite environment control systems concerned with real-time feedbacking of plant response. To achieve these, warming systems, ventilation fans, CO_2 supply system, and other control equipment should be efficiently harmonized together.

In this study, Japanese tomato "Momotaro" were cultivated in glass greenhouse from November 2017 to May 2018 to investigate the complex relationship between environmental factors including temperature, light intensity, humidity, and CO_2 concentration, and their growth. The data recorded during cultivation were used to compute and develop mathematical relations for describing the growth and development of tomato plants in greenhouse conditions.

2. Materials and methods

2.1. Preparation
Glass greenhouse: Tomato cultivation was conducted in the experimental greenhouse in Saga University, Japan, which was 66.43 m^2 of floor area (9.1 m in length x 7.3 m in width, and 4.5 m in height) covered by the glass with a stainless-steel frame. Automatic skylight controlled by temperature and slide-glass windows covered with 1mm mesh screen were equipped. A warming system was also set for the winter season for keeping 16^0C as minimum temperature.

Tomato plants: Subjected cultivar was Momotaro. There were 48 seedlings planted into 4 beds (4 m in length, 0.35 m in width, and 0.2 m in depth). The distance between 2 adjacent plants is 30 cm with 6 plant/m^2 in density.

Cultivation system: Tomato was cultivated by the original solution culture system using porous solid medium, namely Isolite CG that was produced by baking diatomaceous earth and had porous structure whose weight is less than 0.6 kg/litter, water absorption rate = 70 – 80 g/100 g; pH = 6 – 8; chemical composition: SiO_2 = 75 – 80 %, Al_2O_3 = 10 – 12%, Fe_2O_3 = 4 – 6%. Nutrient solution was supplied by micro-irrigation tube simultaneously by controlling timer.

Supplement of carbon dioxide: During cultivation, about 1200 ppm of pure CO_2 was supplied in every morning and the air was circulating by small fans.

2.2. Observations
Environmental factors in the greenhouse as CO_2 concentration, temperature, light intensity, and humidity were monitored by sensors: RTR-576 Wireless CO_2 Recorder and RTR-574 Illuminance UV Recorder. CO_2 sensors were set at the middle of tomato canopy where photosynthesis capacity was normally high. Radiation sensors were set up at the upper (2 m) and lower (1 m) parts of tomato canopy to monitor the intensity of incoming radiation and to observe the shade of the plants.

Plant growing parameters as stem length, number of internodes (the distance between two adjacent leaves-petiole) were measured every 2-week (14 days). The first measurement of stem length (cm), the number of internodes and clusters were done 27 days after transplanting (DAT). The length of the stems was measured from the bottom to the growing tip by using a wire ruler. The numbers of flowers and fruits were counted on each cluster, from flower blooming to fruit harvest. The increases of stem

length, the number of internodes, and the number of clusters were estimated by the difference between two adjacent measurements within 2-week intervals. Clusters on each tomato plant were numbered to the order of their occurrence. The 4-CPA (4-chlorophenoxy-acetic acid) was used to enhance the pollination of flowers. The following dates were recorded: clusters came, flowers bloomed (when flowers start opening) as pollinated, fruit started ripening (when fruits begin changing in color, the 2nd stage), and harvesting time (when fruits were at the 5th stage). Fruits were harvested by using the color chart when fruits turned into light red [4]. Fruits weight (g) was measured with the electrical scale. Fruit yield per plant was determined as summed fruits weight.

2.3. Calculations

Cumulative heat units (CHU): Heat unit (HU) was estimated from the average centigrade temperature of each day over a period as in formula (2.3.1), and then CHU was calculated by taking the sum of HU as in formula (2.3.2) [5].

$$HU = \frac{T_{max} + T_{min}}{2} - T_{base} \tag{2.3.1}$$

$$CHU_i = \sum_{i=1}^{n} HU_i \tag{2.3.2}$$

Where, T_{max} and T_{min} were the daily maximum and minimum temperatures, T_{base} was base temperature (the cool temperature at which a plant does not develop. At or below the base temperature, plants no longer develop leaves and progress towards flowering ceases) of some varieties including tomato, *i* indicated day, *n* was a specific period (day) of plant growth during cultivation; and HU_i was the heat unit on *ith* day (^0C). Any temperature below T_{base} was set to T_{base} before calculating the average. If the mean daily temperature is lower than the base temperature, then HU = 0.

Cumulative light intensity (CLI): CLI was the sum of daily luminance intensity (LI) come into a greenhouse during the specified period of cultivation as in formula (2.3.3) [6].
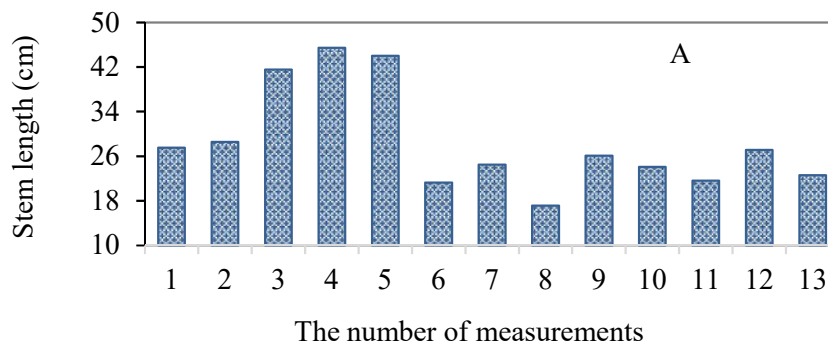
$$CLI_i = \sum_{i=1}^{n} \sum_{h=1}^{24} LI_i \tag{2.3.3}$$

Where, *h* is the hour of the day, LI_i is the light intensity on the *ith* day (lm/m^2).

Development of mathematical relations: The mathematical relations between growing parameters (dependent factors) and environmental variables (independent factors) were examined by R 3.5.1 developed by R Core Team [7]. The significance of the correlation coefficients in models were checked by F-test.

3. Results and discussion
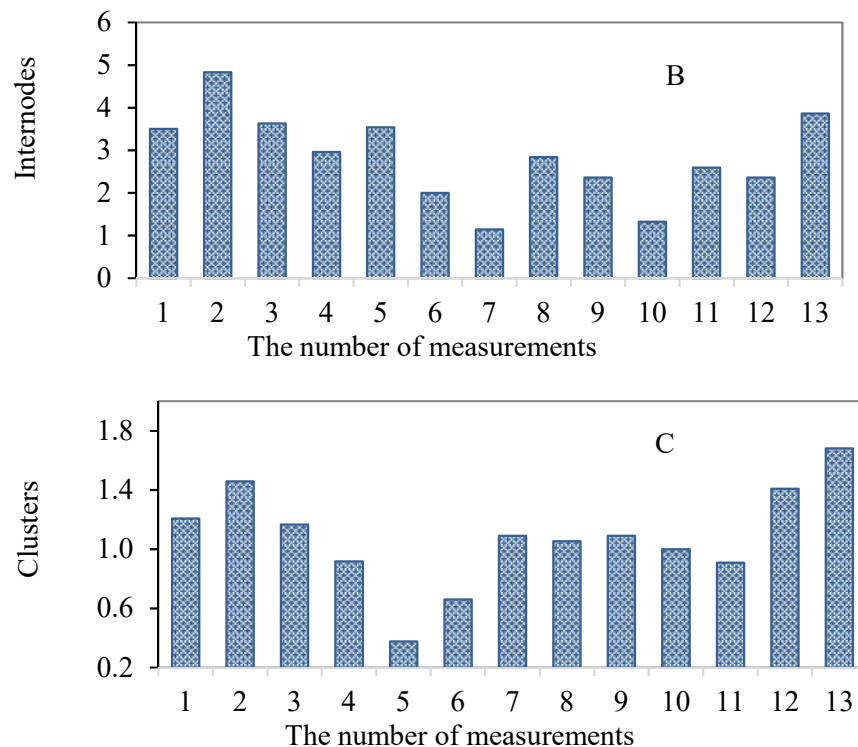
3.1. Tomato growing parameters

Figure 1. The result of tomato growing condition by the number of measurements for every parameter, increase in stem length (cm) (A), internodes (B), and clusters (C) from 29 Nov. 2017 to 30 May 2018.

Figure 1A indicated that increase speed of stem length was gradually rising and reached over 40cm during 3rd to 5th measurement as from 69 DAT to 97 DAT, after that decreasing. Numbers of internodes were quickly increasing and reached highest 4.8 at the 2nd count as 55 DAT, and maintained around 3.5 until 5th as 97 DAT. This result might reveal that firstly numbers of internodes increase, after that each internode grows, then total stem length extended. Therefore, keeping an increasing speed of the number of internodes might be a key factor of the stem extends. For clusters increasing, the highest value was recorded at the last measurement (209 DAT), at 1.68 (figure 1C). At the end of cultivation, total stem length, number of internodes, and clusters were 413.09 ± 24.48 cm, 50.14 ± 2.92, and 15.36 ± 1.26, respectively.

Generally, floral bud comes after every 3 leaves expanding and there was a direct relationship between the number of flowers and yield. On the other hand, if the clusters in the low region were well promoted, vegetative growth and floral buds of upper parts would be declined and suppressed. Therefore, the stable controlling on numbers of flowers relies on the allocation balances between the total number of fruits and vegetative growth. Results of figure 1C was representing these phenomena.
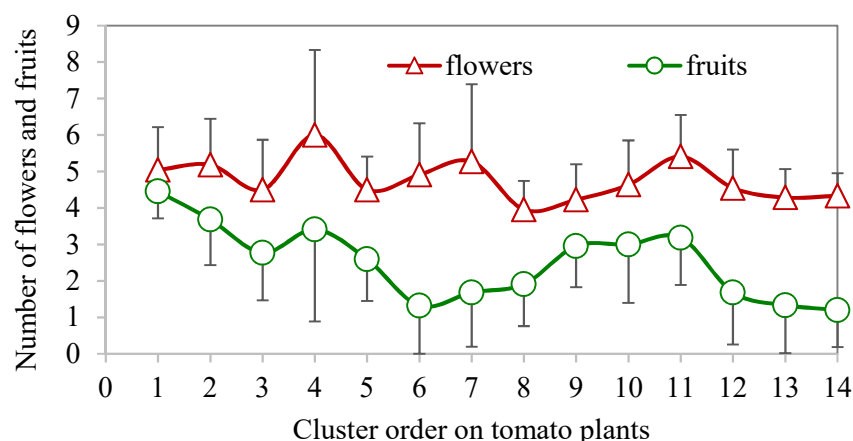
Figure 2. The numbers of flowers and fruits on every cluster on tomato plants.

Figure 2 indicated the numbers of flowers and fruits on every cluster. It showed that the average number of flowers on each cluster fluctuated from 3.95 (cluster 8) to 6.0 (cluster 4). Meanwhile, the averaged number of fruits per cluster ranged from 1.2 (cluster 14) to 4.45 (cluster 1). In cluster 6 and 7, these indicated the lowest range as 1.32 and 1.38 respectively. The ratio of flowers to fruits was not homogeneous among clusters whose moderate correlation coefficient was 0.46.

Hence, this result might reveal that balances between vegetative growing and fruiting were not constant because any environmental factors might have been impacted on the growth and development of tomato growing.
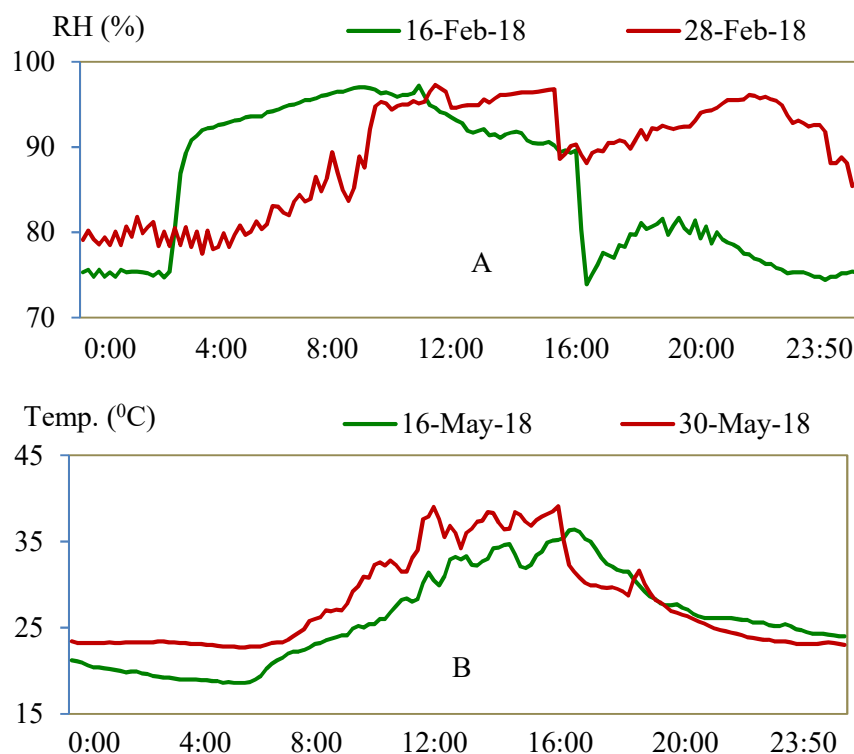

Figure 3. The fluctuation of environmental conditions for cluster 6 and cluster 7 as the RH, for cluster 13 and cluster 14 as the temperature at their fruiting terms.

To confirm such effect by environmental condition, figure 3A indicated relative humidity for 16th February and 28th February when cluster 6 and 7 indicated lowest numbers of blooming and fruiting.

In this term, RH in the glass greenhouse arrived above 80% (figure 3A). High levels of RH (above 70%) during pollen shed will cause a poor or incomplete pollination of tomato flowers [8]. Figure 3B indicated temperature for cluster 13 and cluster 14, which occurred higher and arrived at 32^0C in day-time and 21^0C at night-time. This might be one of the reasons why the proportion of flowers that became fruits declined substantially.
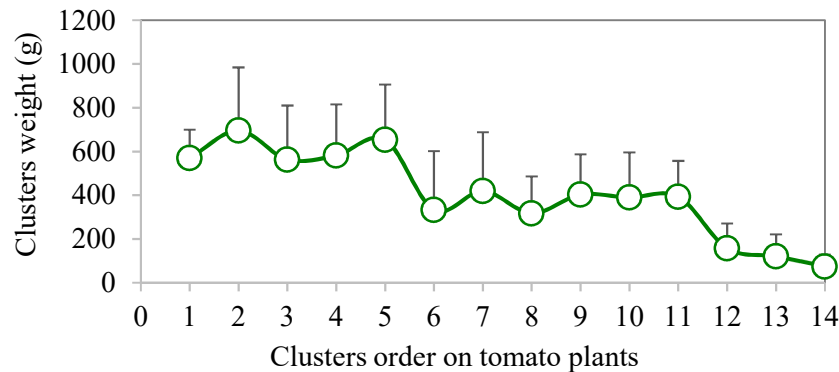

Figure 4. Fruit weight (g) on each tomato cluster.

Figure 4 showed total weight of every cluster. Although the first and second highest number of fruits were cluster 1 as reached 4.45 fruits and cluster 4 as 3.41, the highest weight of clusters was cluster 2 as 696.31 g and cluster 5 as 653.58 g. These results showed these weights tended to decrease during cultivation. It was assumed that the cultivation temperature was gradually rising. Basically, tomato fruit maturation is determined by cumulative temperature. It means if temperature became higher, flowers bloomed faster, fruits ripened earlier, and finally, the size of fruits was smaller [9-12].
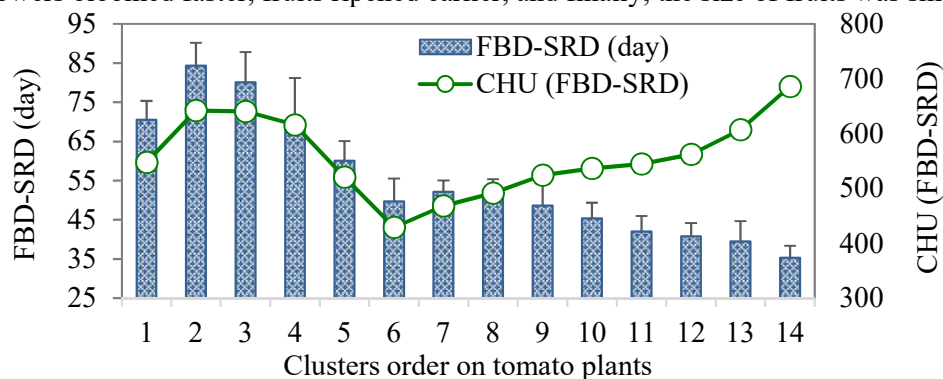

Figure 5. The duration and CHU for flowers become mature fruits.

Figure 5 showed CHU and duration from flowers bloomed date (FBD) to fruits start ripening date (SRD). It indicated that if CHU was gradual increasing, FBD-SRD was decreasing in time for fruits maturation. For example, first fruits of clusters 2nd took the longest time with 84.4 ± 5.8 days for maturation, meanwhile, first fruits of clusters 14th took the shortest time, 35.3 ± 3.1 days for their ripening.

In this study, tomato fruit yield was calculated by summing all the weight of all clusters on the corresponding plant. Figure 6 showed the total yield of every tomato plant. Yields from every plant were widely varied, which reached highest at plant number 11 as 7.34 kg, lowest at plant number 19 as 3.73 kg. Total averaged yield was estimated at about 31 kg/m² and 5.56 kg/plant. The difference in fruit yield among tomato plants could be explained by the difference of environmental condition, the position of tomato plants on cultivation beds, fungal infection, ununiform distribution of solar radiation.
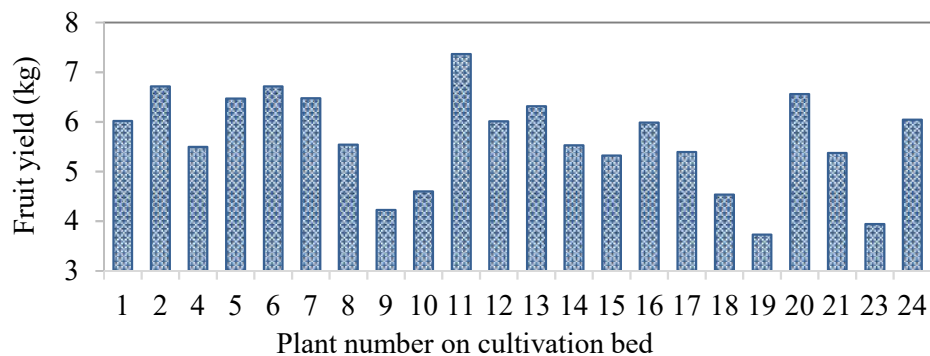
Figure 6. Fruit yield (g) per plant at the end of cultivation.

3.2. Developing relationships

Table 1 presented several types of the mathematical models by using growing indices and environmental factors using simple linear regression model as in equations (1, 2, 4, and 7), multiple linear regression as in equation (6), and polynomial regression as in equations (3 and 5).

Table 1. Results of different equations present the relationships.

Relationships	Equations	R^2	P-value
Increase in stem length (y) and CHU (x)	(1) $y = 16.7 + 0.05x$	0.28	< 0.05
FBD-SRD (y) and CHU (x)	(2) $y = -1.66 + 0.11x$	0.3	< 0.001
	(3) $y = 56.99 + 142.2x + 24.94x^2$	0.32	< 0.001 < 0.1
SRD-HD (y) and CHU (x)	(4) $y = 1.09 + 0.07x$	0.27	< 0.001
	(5) $y = 9.22 + 32.68x + 15.14 x^2$	0.33	< 0.001 < 0.001
SRD-HD (y) and CHU (x_1), CLI (x_2)	(6) $y = 5.496 + 0.082 x_1 - 7.5*10^{-7} x_2$	0.67	< 0.001 < 0.001
Cluster occurrence (y) and CHU (x)	(7) $y = 6.37 + 0.074x$	0.69	< 0.001

Note:
  FBD: flower blooming date;
  SRD: start ripening date;
  HD: harvesting date;
  The increase of stem length was in *cm*;
  FBD-SRD, SRD-HD, and cluster occurrence were in *days*.

First five equations indicated less relationships between the increase in stem height and CHU ($R^2 = 0.28$, $p < 0.05$); the duration of FBD-SRD and CHU ($R^2 = 0.3$ and 0.32, $p < 0.001$ and $p < 0.1$); and the duration of SRD-HD and CHU ($R^2 = 0.27$ and 0.33, $p < 0.001$). The last two equations represented moderate significant relationships by F-test between the duration of SRD-HD and CHU + CLI ($R^2 = 0.67$, $p < 0.001$), the cluster occurrence and CHU ($R^2 = 0.69$, $p < 0.001$).

These results showed that there were some relationships among tomato growing parameters and temperature (CHU). These mean that tomato stem length increased during cultivation by increasing numbers of internodes and their extension, and flowers translated into fruits by cell division progressing. Then new coming clusters were regulated by the temperature, which was related to cell division and cell enlargement.

In addition, temperature and light intensity have been shown a larger influence on tomato fruit ripening. Solar radiation absorbed during cultivation is one of the important factors for tomato plants.

Our results indicated CLI and CHU had a moderate relationship between SRD and HD. It means radiation and temperature controlling will be essentially important to control tomato ripening stage. For a certain level of CLI, if CHU increase, the duration from FRD to HD also increases. Contrary, for a certain level of CHU, the duration from SRD to HD decreases if the CLI units increase as in equation (6). If CHU is increased, then the cluster occurrence increases at a higher rate as in equation (7).

4. Conclusions
These study presented the impacts of environmental factors on the growth and development of tomato plant in greenhouse conditions and the ability to build models for describing these relationships. There were significant linear correlations between the increase in stem height (cm) and cumulative heat unit (CHU), among the time required from flowers bloomed to fruits start ripening, harvest stage and CHU, SRD-HD (start ripening date to harvesting date) and cumulative light intensity (CLI), between clusters occurrence time and CHU. These relationships provide important information for feedbacking to construct ideal cultivation conditions of plants.

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