ESTABLISHMENT OF THE MATHEMATICAL MODELS FOR TOMATO GROWTH INDICES USING ENVIRONMENTAL FACTORS

環境要因に基づくトマト生育指標の数理モデル構築

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Sincerely,

CUONG CHI DOAN

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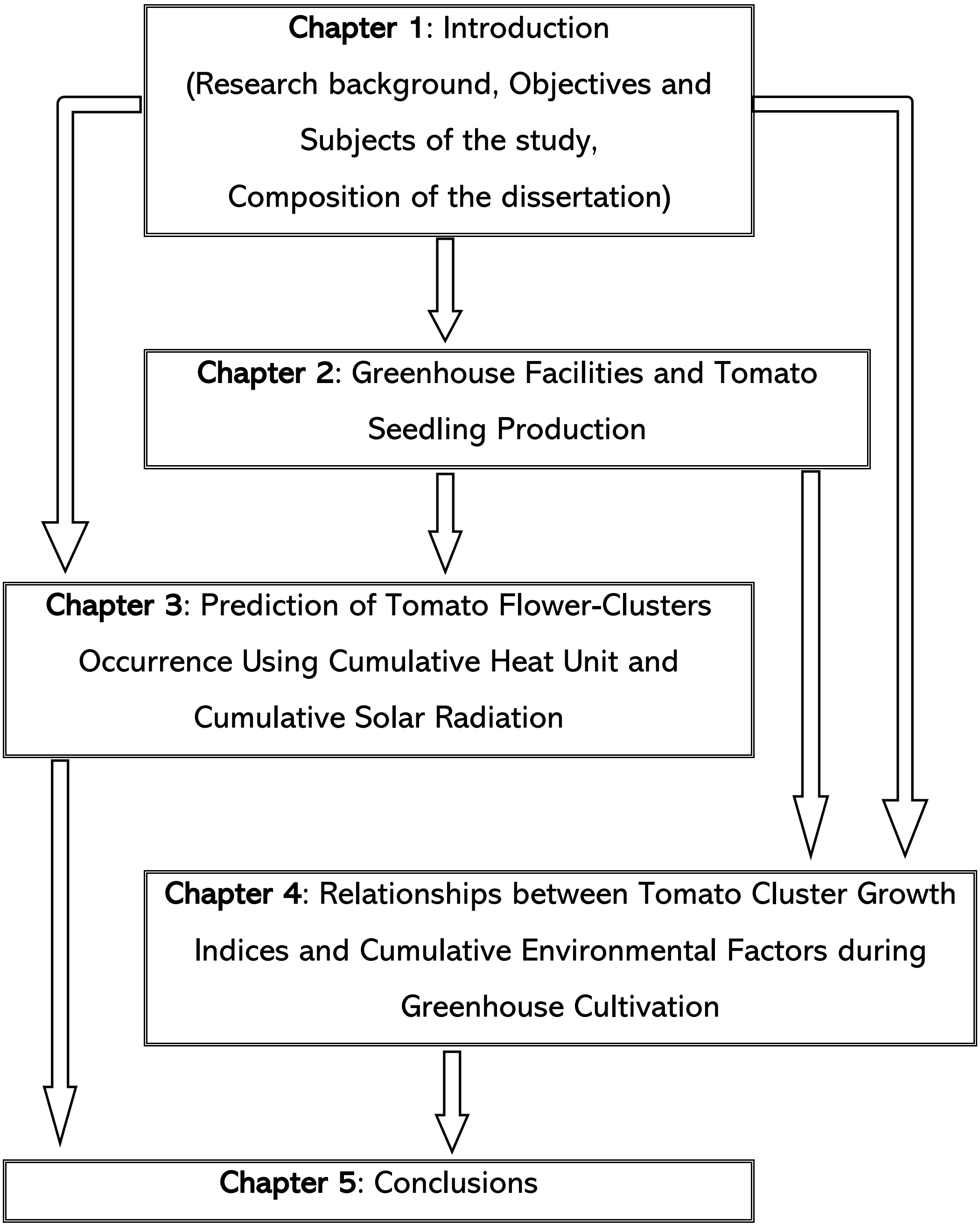
SUMMARY

Tomatoes is an important fruit of high economic value in all over the world due to its special character as a high-yield crop among other commonly consumed fruit-vegetables. In horticulture, tomatoes have considered as model plant for studies on the growth of vegetative and fruit development, including fruit maturing mechanism and postharvest ripening. To identify tomato growth periods, confirmation of flower clusters occurrence is important because the date of first cluster coming will be valid as the base date for counting duration of each growth periods. Furthermore, tomato clusters are continuously and regularly produced on the stems; thus, the growth stages between every cluster overlap, and these growth conditions are gradually dissimilar. Therefore, to presently comprehend tomato growth conditions, precise estimation for every tomato cluster is critically required. Thus this study investigated the effects of environmental factors such as temperature, solar radiation, humidity, and their cumulative indices as the cumulative heat unit (CHU), the cumulative solar radiation (CSR) and vapor pressure deficit (VPD) related to duration of flower-clusters occurrence (DFO), the opening of flower-buds (OB), the maturation (FM), and the ripening of fruits (FR), the number of flowers (NFl), number of fruits (NFr), fruit perimeter (PFr), and the fruit-cluster weight (CWt) by mathematical models using multiple linear regression (MLR). Temperature, humidity, and solar radiation are environmental indices that easy to record and monitor. However, they vary and fluctuate substantially with season and time under the undeniable impacts of climate change. Accordingly, simply and directly applying these indices for evaluating, describing, and predicting the plants' physiological reaction is unreliable and inaccurate. However, this study proves that if these variations are equalized using CHU, CSR, and VPD, they are potential indices to describe and predict the growth characteristics of tomato clusters through mathematical models. CHU and CSR had a significant impact on the occurrence of flower-clusters (r^2 = 0.94, RMSE = 0.71), especially CSR indicated stronger effect on NFl rather than CHU and VPD. There was a strong significant relationship between CHU and DFO (r^2 = 0.93, RMSE = 0.73). Meanwhile, NFr relied much on VPD than CHU and CSR. Also, pollination condition was sensitive to VPD, NFr and FR were important factors in fruit-cluster weight (CWt). MLR models could explain growth indices of tomato cluster with the coefficient of determination (R^2) from 0.742 to 0.953. These mathematical models via MLR indicated that CHU was the most important factor in DFO and PFr, CSR was the significant variable for NFr in each cluster, and VPD was the crucial factor for NFr on each cluster and CWt. These models can be applied to well-controlled environmental conditions during greenhouse cultivation to attain the desired fruit yield at a specific time and fulfill market demand.

LAYOUT AND FLOW OF THE DISSERTATION



Chapter 1

INTRODUCTION

1.1. Overview of environmental factors in tomato greenhouse cultivation

1.1.1. Temperature and cumulative heat unit

Temperature is the driving force for all biological activity (Rowbury, 2003). Consequently, the growth, development and reproduction of many organisms are predictable based on temperature. For tomato greenhouse cultivation, maintaining an optimum average daily air temperature is crucial for entire plants growth, anther development, and successful pollination of pollen in tomato flowers. However, the optimal air temperature depends on different growth stages of tomatoes and light conditions.

The air temperature around $22^{O}C$ was recommended as optimum for leaves development, from $25^{O}C$ to $26^{O}C$ was good condition for fruits growth and fruit set (Sato, Peet, & Thomas, 2000). A temperature between $18.3^{O}C$ and $32.2^{O}C$ are considered to be preferable air temperatures during the entire growing season of tomatoes and values between $10\text{-}35^{O}C$ are the lower and upper marginal temperature for greenhouse tomatoes (Hochmuth, 2012). For ensuring physiological functions, greenhouse tomato requires an average temperature difference between day and night among 5 and $7^{O}C$ with an average of 6 hours light per day (FAO, 2013). It was observed that the optimum air temperature for tomato flowers pollination is about 26°C and progressively failed with temperature reaching 32^{O}C. For the appearance of leaves and clusters the lowest tolerable and optimum air temperature should be maintained around 7^{O}C and 22^{O}C, respectively. In addition, for the development and maturation of tomato fruits, a base temperature of 5.7^{O}C and an optimum temperature of 26°C are required (Adams, Cockshull, & Cave, 2001). The air ambient temperature surrounding tomato canopy should be kept around 30^{O}C to achieve the highest photosynthesis activity, and a temperature between 6-8^{O}C is considered as the base air temperature of tomato leaves (Duchowski & Brazaitytë, 2001).

Plants require a specific amount of heat to develop from one point in their life cycle to another, from sowing to harvest. Heat unit (HU) is a measure of heat above a threshold for that day. Heat unit accumulation reflects the number of heat units above a base temperature for consecutive 24-hour days. It is the departure from the mean daily temperature above the base temperature. An important aspect of HU is that no units are associated with the value. Instead, the accumulated HU values can be correlated with an event in an organism's life. The HU concept was proposed to explain the relationship between growth duration and temperature. The concept assumes a direct and linear relationship between growth and temperature.

The first use of HU in agriculture was to predict the maturity in corn (Gilmore Jr. & Rogers, 1958). Then, the HU concept was widely used for many crops grown in greenhouses and opened field with various applications. It was applied to determine the growing season's length (Elnesr, Alazba, & Alsadon, 2013; McMaster & Wilhelm, 1997; Russelle, Wilhelm, Olson, & Power, 1984), to predict grain moisture (Swan, Schneider, Moncrief, Paulson, & Peterson, 1987), crop yield, length of plant stages (Miller, Lanier, & Brandt, 2018; Nielsen & Hinkle, 1996; Ramesh & Gopalaswamy, 1991), flowering date and maturity timing (Akyuz, Kandel, & Morlock, 2017), harvesting date (Villordon, Clark, Ferrin, & LaBonte, 2009), and fertilizer availability (Griffin & Honeycutt, 2000).

The HU term was proposed to describe the relationship between growth duration of a plant and temperature. It is derived from the mean daily temperature and subtracting it from the base temperature needed for crop's growth. The initial HU value for a particular day is represented by the following equation 1.1:

$$HU_i = \left[\left(\frac{T_{max}+T_{min}}{2}\right) - T_{base}\right]_i \qquad (1.1)$$

where, T_{max} is the daily maximum temperature, T_{min} is the daily minimum temperature, and T_{base} is temperature below which the plant does not grow or grows very slowly (the enlargement and elongation speed of stems are small, the extension of fruit cells in a specific period is slow comparing to the other periods had higher in temperature).

Because there are limitations of the initial HU concept like it assumes a direct and linear relationship between growth and temperature while the actual relationship is curvilinear, it gives more importance to higher temperatures although it is detrimental to growth, the diurnal variation is not considered though it has considerable influence on growth, and without any gaps are made for base temperature changes although the base temperature varies from crop to crop, stage and seasonal conditions of the crop.

Therefore, modifications of initial HU were proposed to enhance its biological meaning to a particular organism and reduce its limitations as well. It was involved in an upper threshold and ceiling temperature (K.B. Perry, Wehner, & Johnson, 1986; Katharine B. Perry et al., 1997), converted to the photo-thermal units by adding a photoperiod represented as daylength (Masle, Doussinault, Farquhar, & Sun, 1989; Perry et al., 1993), transferred to the helio-thermal unit by adding the actual sunshine hours (Patil, Jadhav, & Jadhav, 2014), or HU was combined with relative humidity called as hydro-thermal unit (Ahmad, Habib Kanth, Parvaze, & Sheraz Mahdi, 2017).

1.1.2. Light intensity and cumulative solar radiation with growing of greenhouse tomatoes.

Light intensity refers to the total amount of light that plant receives. In contrast to light quality, description of the intensity of light does not consider wavelength or color. Light intensity is often measured by the unit lux (lx or lumens.m^{-2}) which merely is based on visual sensitivity and do not provide information on the energy of the photon content. Conventional units of light intensity for studies involving plant responses are µmol.m^{-2}.s^{-1} and MJ.m^{-2}.day^{-1}. These units describe the number of photons of light within the photosynthetic waveband (400–700 nm) that an area of 1 m^2 receives per second, and the other is the amount of energy (in joule) that plants receive per day in an area of 1 m^2.

In addition to the temperature conditions, solar radiation is also a key factor in influencing tomatoes growth (Perin et al., 2018). During tomato cultivation, plant size (height of plants, number and size of leaves) and total biomass increase, while the amount of solar radiation remains constant (in our study, this values were around 11.2 $MJ.m^{-2}.day^{-1}$ in October, 9.0 $MJ.m^{-2}.day^{-1}$ in December, and 23.5 $MJ.m^{-2}.day^{-1}$ in June), thus the concentration of photosynthetically active radiation (PAR) per leaf area decreases. This means that light intensity is a limiting factor of plant growth, as photosynthetic efficiency is restricted by the intensity of solar radiation. Cumulative solar radiation (CSR) is the total amount of photosynthetically active radiation over 24 hours. PAR varies, depending on latitude, season, clouds, greenhouse location and transmissivity of greenhouse covering materials (Barkat, Zhong-Hua, & Subbu, 2019).

CSR strongly impacts photosynthesis and respiration through the leaves and showed a positive correlation with tomatoes productivity and growth rate during cultivation (Faust, Holcombe, Rajapakse, & Layne, 2005). CSR was used to assess the regulation of photosynthesis and transpiration processes, evaluate the tomato growth and its yield during cultivation (Driss et al., 1995; Jiao et al., 2019; Leonardi et al., 2000; Lu et al., 2015). Previous studies have investigated CSR that tomatoes perceived from anthesis to harvest influenced the total yield of single-truss tomatoes (McAvoy et al., 1989), The number of harvested fruit and the yield of tomatoes were significantly and positively correlated with solar radiation during the days before anthesis and CSR could predict weekly tomato yield in a commercial greenhouse (Higashide, 2009). Supplement light for underneath or within the inner tomatoes canopy have significantly promoted leaf photosynthetic activities, plant growth, and fruit production in plants exposed to low solar irradiation levels, from 0 μmol $m^{-2}.s^{-1}$ to 200 μmol $m^{-2}.s^{-1}$ (Jiang et al., 2017). Although there was not different in yield and photosynthetic capacity between the three photoperiods in the study of Leonardi, however, there was a tendency to have higher yields under longer photoperiods (Leonardi, Guichard, & Bertin, 2000).

The concept of radiation threshold refers to the minimum value of daily global solar radiation by which the production of carbohydrates by photosynthesis would be sufficient to promote plant growth (Perin et al., 2018). This means plants will not accumulate enough dry matter and not develop properly in low solar radiation availability under the compensation point. Despite the fact that FAO recommended the minimum solar radiation threshold crops is 8.46 MJ $m^{-2}.d^{-1}$ (FAO, 2013), a value of 3.6 MJ $m^{-2}.d^{-1}$ was proved as the minimum threshold for mini greenhouse tomatoes (Perin et al., 2018). In another study, the number of tomato fruits per square meter was reported not differ significantly between the unshaded control (12.4 MJ $m^{-2}.d^{-1}$) and shaded (5.0 MJ $m^{-2}.d^{-1}$) tomato plants from solar radiation. However, at the dry biomass from unshaded and shaded tomato plants were different significantly. Total plant growth was reduced to 21.7% by shading, but plants continued to grow, in spite of the radiation level below the trophic limit of 8.4 MJ $m^{-2}.d^{-1}$ (Sandri, Andriolo, Witter, & Dal Ross, 2003).

1.1.3. Relative humidity and vapor pressure deficit in greenhouse tomato cultivation

Total greenhouse humidity is the result of condensation on the covering, vapor losses from ventilation and the balance between plants transpiration and soil evapotranspiration. It is expressed in scientific literature as absolute humidity (g/m^3) or relative humidity (%); in which relative humidity (RH) is used more common (Shamshiri et al., 2018). RH is normally expressed when referring to the air moisture. It is indicated as the percent water vapor in the air in comparison to the total amount of water that could be held by the air if it were saturated. Humidity affects plant water status, which in turn influences all processes related to transpiration, including ion translocation, water balance and transpiration cooling. This RH is the most common way of considering humidity levels, however, it is not the best measurement to accurately predict plant transpiration or water loss because the amount of water that air can hold varies with temperature, warmer air has a greater water-holding capacity than cooler air (Shamshiri et al., 2018). The water holding capacity of air approximately doubles with every 20 ^{0}F increase in temperature.

Vapor pressure deficit (VPD) is defined as the actual difference between the actual vapor pressure and the saturation vapor pressure (Abtew & Melesse, 2013), that calculated as the following equation 1.2:

$$e_s = 0.611exp\left(\frac{17.27T}{T+237.3}\right)\ ;\ VPD = e_s\left(1-\frac{RH}{100}\right) \qquad (1.2)$$

where e_s is saturation vapor pressure (kPa) and T is the air temperature in Celsius (^{0}C).

In the field of crop sciences, it is the difference in vapor pressure between the inside of the leaf compared to the vapor pressure outside of the leaf. The inside of the leaf is always wet and outside is drier, hence, the leaf will try to equalize the vapor pressure through transpiration, leading to the release of water vapor through the stomata. VPD is often measured in pounds per square inch (psi) or kilopascal (kPa) and its value is independent of temperature.

Thereby VPD can provide information about plant transpiration, it is used as an important indicator of the vapor pressure stress on plants, estimate the condensation potential of a greenhouse crop and identify when it is likely to occur. Hence, it is the main parameter for controlling plant water uptake that affects other processes such as photosynthesis, pollination, growth, and yield. VPD is the driving force for water movement between roots and leaves, related to the transpiration, quality and yield of tomato fruits (Shamshiri et al., 2018).

The air with a high RH, greater than 85%, can provide an environment conducive for fungal pathogens because the water lost through the stomata is slowly lost to the air and, therefore, remains on the leaves. Low RH and high temperature usually will result in increasing VPD, which in turn heightens stomatal resistance and increases transpiration; induced midday depression in stomatal conductance for CO_2 diffusion, which led to a decline in net photosynthetic rate (Dorais, Demers, Papadopoulos, & Ieperen, 2003). It was reported that almost tomato varieties grown in greenhouses, RH range between 60-90% is considered appropriate throughout cultivation. The optimal range of RH during growth stages of tomato is suggested to be between 50-70% and pollination process of tomato flowers is significantly enhanced when RH is around 60% during cuiltivation (Harel, Fadida, Alik, Gantz, & Shilo, 2014).

A long-term adaptation to depressed photosynthesis in response to high VPD inside the greenhouse can limit plant growth, dry matter accumulation, and hence decrease yield (Guichard, Bertin, Leonardi, & Gary, 2001; Leonardi, Guichard, & Bertin, 2000). Similarly, low VPD is associated with reduced plant transpiration, causing dehydration, wilting and necrosis. Extreme humidity affects both plant vegetative growth and fruit quality and increases the likelihood of disease (A.P., André, & Gosselin, 2000; Barkat, Zhong-Hua, & Subbu, 2017; Santosh, Tiwari, Singh, & Reddy, 2017). Tomato fruits grown at high humidity generally have a shorter shelf life because they become soft more quickly (Leonardi, Guichard, & Bertin, 2000).

For reducing the drying of young plants and keep plants hydrated when transplanting into greenhouses, fairly low VPD of 0.3 kPa is normally required

(Schwarz, Thompson, & Kläring, 2014). However, maintaining a VPD greater than 0.5 kPa in greenhouses while finishing plants, especially when there is a dense plant canopy. Plants will be able to transpire, cool themselves and be less stressed while the environment is less conducive to disease. Too dry of an environment with a very high VPD of 2.2 kPa could cause plant stress and fruit cracking in tomatoes (Leonardi, Guichard, & Bertin, 2000). An increase in VPD from 1 to 1.8 kPa determines the major reduction in plant growth on tomato plants due to the depression of photosynthesis, related to the reduction of stomatal conductance (Grange & Hand, 1987). These are because plant radiation use efficiency is related to VPD (Stockle & Kiniry, 1990).

The water balance of tomato fruits is determined by supplying of sap through xylem and phloem, losing due to back-flow from fruits to other organs, and transpiration of cuticular. Fruit sink activity in terms of water import varies according to the stage of fruit development, and transpiration rate of leaves and fruits. Therefore, high VPD also effects on tomato fruits weight caused by a variation in plant water status, and supply of water to fruits, and by an increased transpiration of the fruit. Water accounts for about 90 – 95% of the weight of ripe tomato fruits, hence, modification of water transfer into and out of the fruits could also have effects on fruit growing (De Swaef, Verbist, Cornelis, & Steppe, 2012; Ho, Grange, & Picken, 1987). A VPD below 0.4 kPa is recommended as the set-point to activate a dehumidification system, and that values over 1.37

kPa should trigger humidification devices, this range is called marginal borders of VPD for greenhouse tomato cultivation (Argus, 2009).

In terms of optimal VPD for tomato greenhouse cultivation, it ranged from 0.3 to 1.0 kPa in different studies. A VPD between 0.2 and 1.0 kPa is recommended for better pollination process growth development of tomatoes (Picken, 1984); a VPD among 0.5 and 0.8 kPa is optimal for glasshouse tomatoes in preventing from yield reduction due to fruit shrinkage and fungus (Barker, 1990); a VPD of 0.8 kPa during the day and night increased photosynthetic rates and tomato fruit yields compared to plants grown with a VPD of 0.5 kPa (Iraqi, Gagnon, Dubé, & Gosselin, 1995); a VDP of 0.97 can result in obtaining higher tomato fruit yield and quality shown by the texture, color, and sugar content (Xu, Iraqi, & Gosselin, 2007). Maintaining optimal VPD enhances tomato fruit quality (high sugar contents and dry matter weight) and help plants avoid from calcium deficiency (Barker, 1990; Gautier, Guichard, & Tchamitchian, 2001).

In greenhouse cultivation, the interaction between temperature, humidity and solar radiation has been reported in studies (Hirasawa, Nakatsuka, Masui, Kawanami, & Shirai, 2014; Mortensen, 2014; Santosh, Tiwari, Singh, & Reddy, 2017). Temperature directly impacts to water availability of plants, because of its ability to modulate plant water use via effects on VPD.

1.2. Tomato production around the world and Japan

1.2.1. The world tomatoes production

Tomato is belonged to the Solanaceae family and is believed to have originated in Peru and Ecuador, the tropical regions of South America. It prefers a relatively dry and cool climate and is vulnerable to high temperatures and humidity, but its growth deteriorates when the amount of solar radiation is low. After being introduced to Southern Europe, it developed as an edible product, especially in Italy. It was introduced to the Asian region by the Portuguese and came to Japan in the early 18th century but was initially ornamental. Production was low until the early Showa era, but as a result of breeding and introduction by paddy field conversion, the production area has now expanded from Hokkaido to Kyushu, and it is considered as a vegetable that is supplied year-round regardless of the season (Agriculture & Livestock Industries Corporation [https://vegetable.alic.go.jp]).

In terms of total production, worldwide 177,118,248 tons of tomato is produced per year. China was by far the largest tomato producer in the world. In 2019, the country produced approximately 61.4 million tons. This was about 3 times more than number two on the list, India, with 19.3 million tons. The U.S.A. was third with 12.64 million tons. Japan stood at twenty-sixth with 720.6 thousand tons (Table 1.1).

Table 1.1. Top 20 countries of tomato production in terms of total production in 2019

No.	Countries	Total production (tons)	Acreage (ha)	Yield/ha (kg)
1	China	61,423,811	1,003,992	56,199.5
2	India	19,289,400	760,000	24,209.2
3	USA	12,638,410	144,410	90,287.4
4	Turkey	11,600,000	188,270	66,925.2
5	Egypt	7,943,285	199,712	39,773.7
6	Italy	6,437,572	103,940	61,935.3
7	Iran	6,372,633	159,123	40,048.4
8	Spain	4,671,807	54,203	86,191.7
9	Brazil	4,167,629	63,980	65,139.6
10	Mexico	4,047,171	93,376	43,342.9
11	Russian Federation	2,986,209	118,451	25,210.5
12	Uzbekistan	2,648,017	61,097	43,341.0
13	Nigeria	2,243,228	574,441	3,905.1
14	Ukraine	2,229,690	74,300	30,009.3
15	Portugal	1,693,860	20,854	81,224.7
16	Tunisia	1,303,000	22,190	58,720.1
17	Algeria	1,280,570	22,556	56,772.9
18	Morocco	1,231,248	15,239	80,794.3
19	Cameroon	1,182,114	92,626	12,762.2
20	Greece	1,044,346	18,042	57,884.0
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26	Japan	720,600	11,600	62,421.5

(Data source: World Processing Tomato Council (WPTC), 2020)

However, in terms of productivity, the Netherlands and Belgium were countries gained highest in yield per hectare, above 500,000 kg/ha (about 50 kg/m^2), followed by United Kingdom with about 416,000 kg/ha (41.6 kg/ha), and fluctuated around 310,000 to 365,000 kg/ha in countries like Finland, Sweden, Iceland, Denmark, Ireland, Norway, and Austria. Japan stood at forty-one with yield reached approximately 63,000 kg/ha (Table 1.2).

Table 1.2. Top countries of tomato production (yield per hectare) in 2019

No.	Countries	Yield/ha (kg)	Acreage (ha)	Total production (tons)
1	The Netherlands	507,042.30	1,775	900,000
2	Belgium	506,904.30	512	259,535
3	United Kingdom	416,189.70	232	96,556
4	Finland	365,955.00	111	40,621
5	Sweden	365,500.00	40	14,620
6	Iceland	359,000.00	4	1,436
7	Denmark	352,666.70	30	10,580
8	Ireland	333,333.30	12	4,000
9	Norway	318,314.30	35	11,141
10	Austria	310,033.40	178	55,068
11	Germany	253,077.20	337	85,287
12	Switzerland	228,070.70	184	41,965
13	France	186,103.40	3,444	640,940
14	Luxembourg	146,428.60	1	123
15	Palestinian Territories	125,451.90	1,765	221,466
16	Kuwait	123,078.30	625	76,891
17	New Zealand	115,369.90	791	91,267
18	Hungary	92,932.90	2,139	198,801
19	USA	90,287.40	144,410	12,638,410
20	Malaysia	86,940.50	2,794	242,946
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41	Japan	62,421.50	11,600	720,600

(Data source: WPTC, 2020)

In terms of tomato production for processing, in the period of 10 years (2011 – 2020), China was the first biggest country in consuming tomatoes with about 5.13 million tons, Italy came second with 4.88 million tons, followed by Spain and Turkey with 2.62 and 2.03 million tons. However, Italy is expecting to continue increasing and cross China in the year 2021 with 5.3 million tons. For Japan, compared to the year 2020, tomato production for processing continue rising in the year 2021 with around 30 thousand tons. Yet, the amount is still lower than the average in 10 years period (2011 – 2020), 36 thousand tons (Table 1.3).

Table 1.3. Top countries produce tomatoes for processing

No.	Countries	Total tomato production for processing (in 1000 metric tons)		
		Average 10 years (2011-2020)	Year 2020	Forecast 2021
1	China	5132.2	5800	5200
2	Italy	4883.4	5166	5300
3	Spain	2624.8	2650	2900
4	Turkey	2034.0	2500	2300
5	Iran	1488.0	1300	1300
6	Brazil	1400.5	1421	1480
7	Portugal	1304.0	1262	1400
8	Chile	892.2	907	1130
9	U.S.A.	857.7	901	470
10	Tunisia	766.8	961	1000
11	Ukraine	563.0	800	800

12	Algeria	503.0	800	800
13	Argentina	422.5	454	540
14	Canada	417.8	438	450
15	Greece	408.9	420	460
16	Egypt	308.5	420	440
17	Russia	247.5	515	550
18	Dominican Republic	236.2	181	227
19	Thailand	216.3	40	40
20	Australia	208.4	210	248
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33	Japan	36.0	23	30

(Data source: WPTC, 2020)

1.2.2. Tomato production in Japan

In Japan, there are about 32 tomato varieties growing throughout the year in 47 reported prefectures. From May to August, it is the best season with the total yield ranged between 40,000 – 45,000 tons, and the annual was about 37,000 tons. Unlike in tropical countries, tomato crop in Japan are mainly cultivated in greenhouse systems (JapanCROPS: [https://japancrops.com]).

The total product (tons) of tomato in Japan decreased by 1.06%, and the cultivation acreage decreased by 10.08% in the period of 2006 – 2019. However, the tomato yield per 10a increased by 9.72% in that period (Table 1.4).

Table 1.4. Tomato production trends in Japan (2006-2019)

Year	Acreage (ha)	Total yield (tons)	Yield/10a (kg)

2006	12,900	728,300	5,660
2007	12,700	749,200	5,900
2008	12,500	732,800	5,860
2009	12,400	717,600	5,790
2010	12,300	690,900	5,620
2011	12,000	703,100	5,860
2012	12,000	722,400	6,020
2013	12,100	747,500	6,180
2014	12,100	739,900	6,110
2015	12,100	727,000	6,010
2016	12,100	743,200	6,140
2017	12,000	737,200	6,140
2018	11,800	724,200	6,140
2019	11,600	720,600	6,210

(Data source: Japan government statics: https://www.e-stat.go.jp)

In the period of 2006 – 2019, Kumamoto and Ibaraki were the prefectures with the largest tomato production area (1,186 and 932 ha, respectively). However, Tochigi, Kumamoto, Aichi, and Gifu were prefectures reached highest yield per 10a (9,414; 9,314; 8,769; and 8,079 kg/10a, respectively). In that period, Saga prefecture stood at thirty-sixth (Table 1.5).

Table 1.5. Top 10 prefectures with high ranking of tomato production in the period of 2006 – 2019 (average 14 years)

No.	Prefectures	Total yield (tons)	Yield ratio (%)	Acreage (ha)	Acreage ratio (%)	Yield/10a (kg)
	Entire Japan	727,946		12,230		5,956

1	Kumamoto	110,730	15.2	1,186	9.7	9,314
2	Hokkaido	56,023	7.7	805	6.6	6,950
3	Ibaraki	47,484	6.5	932	7.6	5,095
4	Aichi	46,096	6.3	525	4.3	8,769
5	Chiba	44,676	6.1	847	6.9	5,267
6	Tochigi	36,023	4.9	383	3.1	9,414
7	Fukushima	27,046	3.7	425	3.5	6,375
8	Gifu	25,830	3.5	319	2.6	8,079
9	Gunma	25,130	3.5	325	2.7	7,706
10	Nagano	21,553	3.0	411	3.4	5,216
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36	Saga	4,520	0.6	77	0.6	5,816

(Data source: Japan government statics: https://www.e-stat.go.jp)

In 2019, Kumamoto and Ibaraki were also the prefectures with the largest tomato production area, 1,250 and 882 ha, respectively. Yet, in terms of the yield per 10a, Kumamoto prefecture has the highest amount of 10,700 kg, followed by Tochigi prefecture with 10,500 kg, Kochi prefecture with 9,460 kg, and Fukuoka prefecture with 8,970 tons. Particularly, Saga prefecture stood at 22nd with 5,640 kg/10a, and the national average was 6,210 kg/10a (Table 1.6).

Table 1.6. Top 10 prefectures with high ranking of tomato production in 2019

No.	Prefectures	Total yield (tons)	Yield ratio (%)	Acreage (ha)	Acreage ratio (%)	Yield/10a (kg)
	Entire Japan	720,600	---	11,600	---	6,210
1	Kumamoto	133,400	18.9	1,250	10.6	10,700

2	Hokkaido	61,000	7.6	814	6.8	7,490
3	Aichi	43,900	6.5	490	4.3	8,960
4	Ibaraki	43,400	6.4	882	7.8	4,920
5	Tochigi	34,800	5.1	331	6.6	10,500
6	Chiba	31,900	5.0	759	3	4,200
7	Gifu	24,200	3.2	309	3.1	7,830
8	Gunma	24,100	3.1	305	2.7	7,900
9	Fukushima	22,400	3.1	357	2.5	6,270
10	Miyazaki	19,300	2.7	223	1.9	8,650
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41	Saga	3,410	0.5	67	0.5	5,090

(Data source: Japan government statics: https://www.e-stat.go.jp)

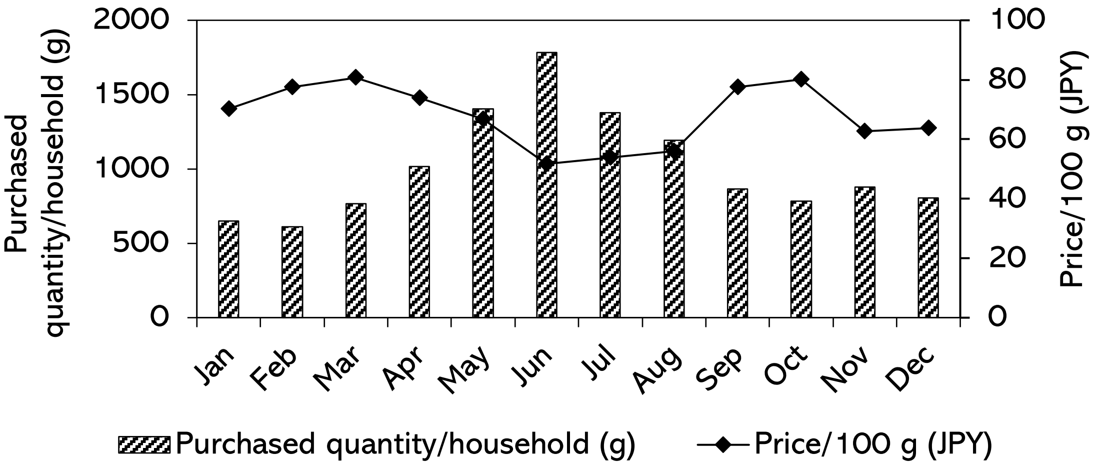

Fig. 1.1. The 13-years (2006-2018) average monthly purchased quantity per household and price per 100 g for tomato in Japan (JapanCROPS: https://japancrops.com)

In the period of 2006-2018, the biggest purchased tomatoes quantity per household was in June with 1782 g, followed by May (1404 g), July (1379 g), and August (1193 g). However, the price of tomato per 100 g was the lowest in those months of the year, about 51.7 to 56.1 JPY/100g. Meanwhile, the highest price were in February, March, September, and October at about 77-80 JPY per 100 grams (Fig. 1.1).

1.3. The objectives and subjects of study

To obtain higher yield productivity per area, and easier in yield estimation for each season, the objective of this study was to delve into impacts of environmental factors such as temperature, humidity, and solar radiation to the growth and development indices of tomato plants growing in greenhouse system, such as the prolongation of stems, the occurrence of bud-clusters, the development of flower and fruit-clusters like the pollination of flowers, the number of flowers and fruits, the maturation and ripening of fruits, the fruit size and weight, and the yield of plants.

Those impacts of environmental factors on tomato plants were established and presented through mathematical models derived from simple, polynomial, and multiple regressions performed by R program and relevant analysis packages.

Findings from those mathematical models are applied and adopted to specify the terms of tomato growing phases, like the coming of bud-flowers, blooming of flowers, maturation and ripening of fruits, and to provide important information of yield predictions from every tomato-clusters.

Lastly, growth and development of tomato indices will be able to predict by setting the desired values of temperature, solar radiation, and humidity through operation warming or cooling equipment, modification light intensity via artificial light, and controlling humidity via a humidifier. Therefore, the achievements of this research will also make significant contribution to optimize environmental condition in the greenhouse for gaining higher tomato productivity and yield.

Following subjects were carried out in each chapter:

1. In chapter 2, we introduce the greenhouse facilities prepared for official tomato cultivation. Besides, steps of tomato seedlings production for transplantation into glass greenhouse are also indicated. Preparation of liquid fertilizer and hydroponic system for tomatoes are presented and described.
2. In chapter 3, we present findings on prediction the duration of flower-cluster occurrence on tomato plants during cultivation using cumulative heat unit and cumulative solar radiation.
3. In chapter 4, the impacts of environmental factors such as temperature, solar radiation, and humidity on tomato growing indices like the number of flowers and fruits, the fruit size, fruit-cluster weight, and

durations of bud-flower-fruit clusters are presented through mathematical models established from simple, multiple, and polynomial regressions analysis computed via R program and relevant packages.

4. In chapter 5, we do conclusions on study results, propose practical applications from those findings, and make recommendations for improvement in other studies.

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Chapter 2

GREENHOUSE FACILITIES AND TOMATO SEEDLING PRODUCTION

2.1. Greenhouse preparation

The greenhouse located at Saga University with around 66.5 m^2 of floor area (9.1 m in length x 7.3 m in width, and 4.5 m in height) covered totally by the glass with a stainless-steel frame and a system of slide-windows at two sides was used for the official tomato cultivation. On top of the roof, there are swing windows operated automatically by a set of thermal sensors to improve the ventilation, circulation, and temperature conditions.

A warming heater was assembled to maintain the air temperature over 15 °C in the winter season, the ventilation condition was insured by 5 fans and sliding windows; in which 2 fans were assembled on the undersurface of skylight windows and automatically operated when the temperature exceeded 25 °C, the other 2 fans put on the top surface of cultivation bed between two planting lines, and the last fan was assembled on the center of the greenhouse ground. All fans were operating at all times. Sliding windows were opened when the ambient temperature exceeded 30 °C. Fluorescent lights were daily switched on from 5 to 7 pm.

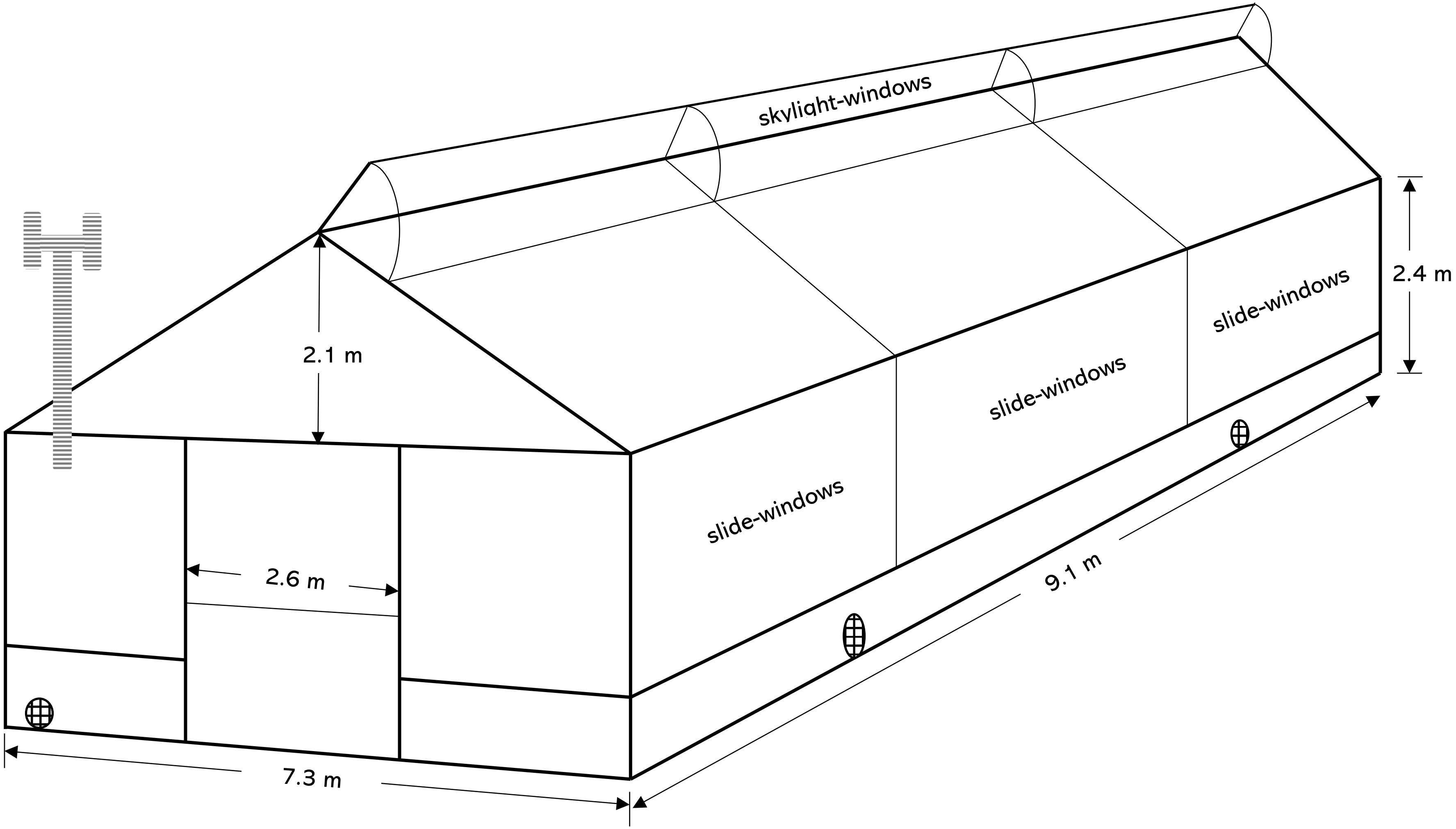

Fig. 2.1. The outside appearance of glass greenhouse

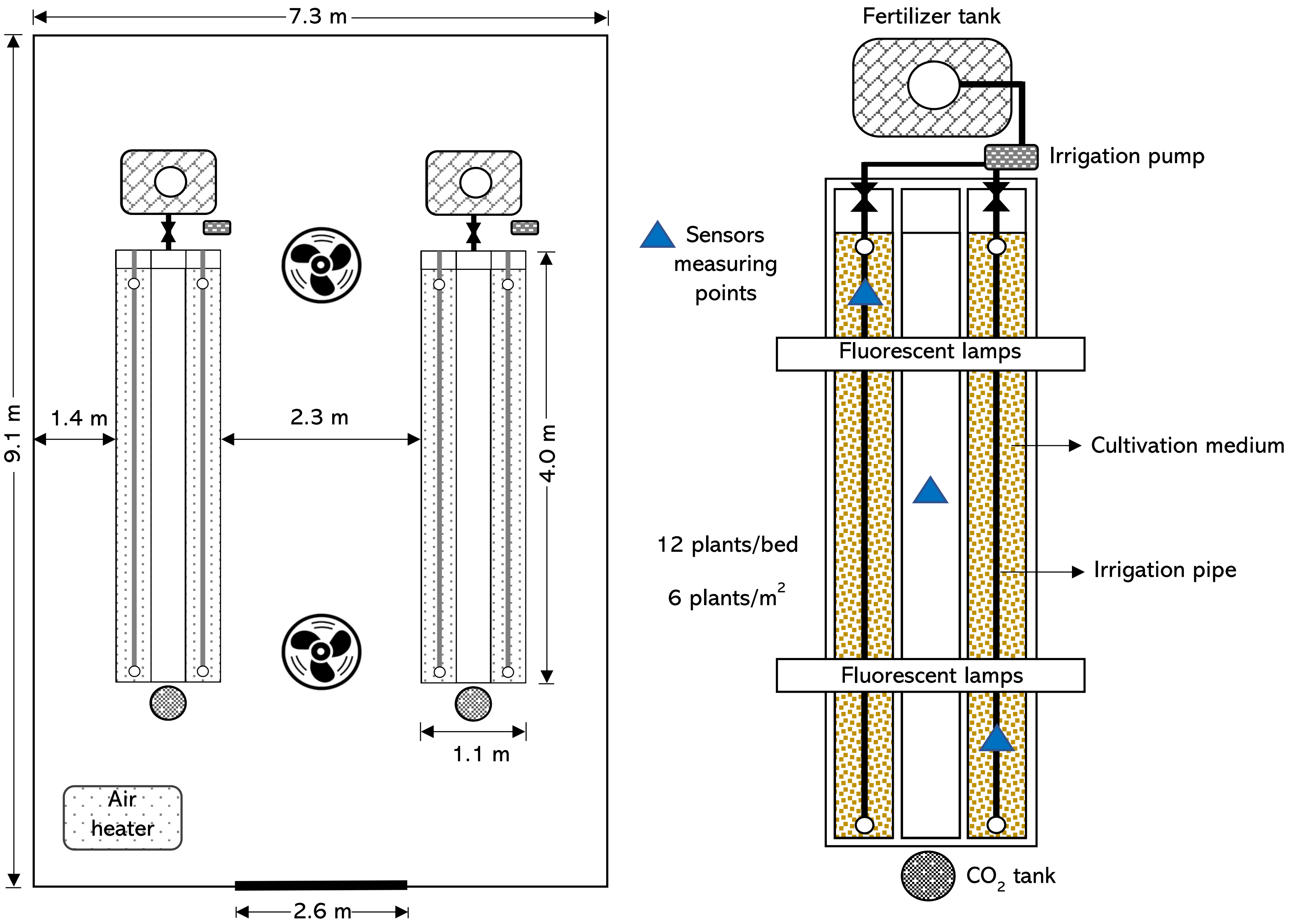

Fig. 2.2. The inside sketch of glass greenhouse

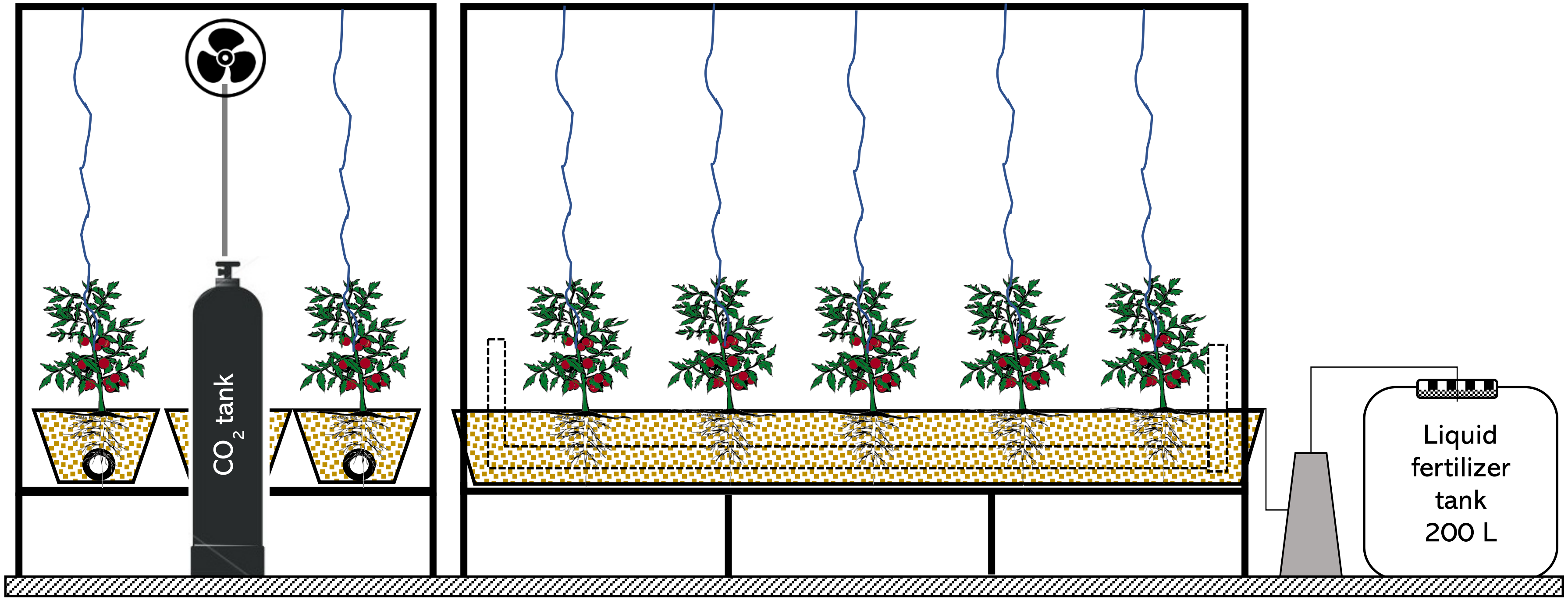

Fig. 2.3. The layout of cultivation beds

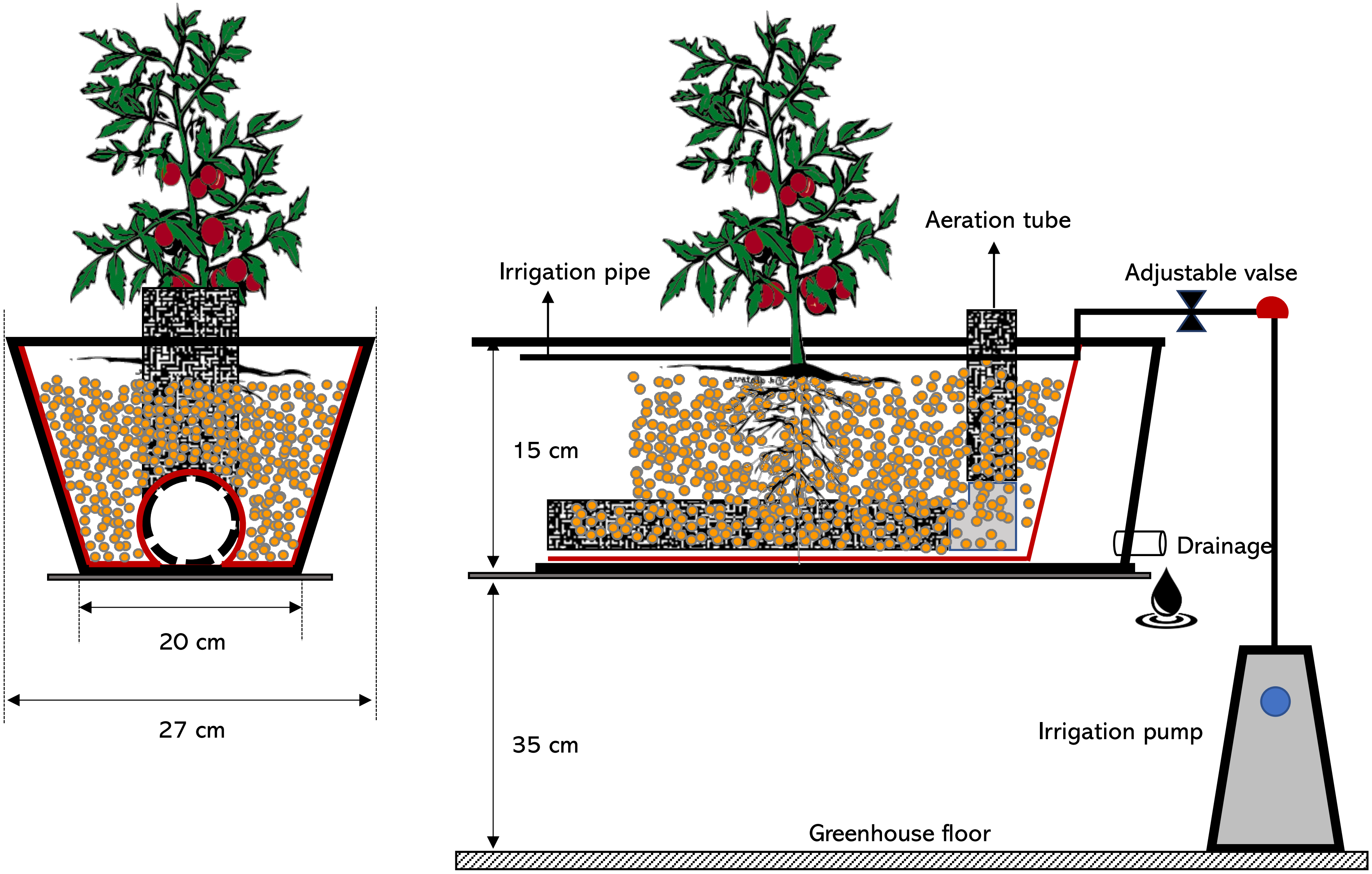

Fig. 2.4. The structure of a cultivation bed

2.2. Cultivation medium and beds

Because seeds are very sensitive to nutrients, as a result, germinating seeds in a nutrient-rich environment can actually cause damage for germination. Common media for seed germination include rockwool cubes, coco coir pods, or a seedling starter fertilizer. In this study, the germination medium used was made from bark and Bora soil with pH = 5.5 – 7, EC = 1 mS/cm.

Fig. 2.5. Germination medium for seeds sowing

2.3. Liquid fertilizer

The liquid fertilizer used for experiment was prepare from commercial fertilizer for hydroponic cultivation of OAT Agrio Co., Ltd. (www.oat-agrio.co.jp), with the composition as Table 2.1.

Table 2.1. Percentage of components in OAT fertilizers use for experiment

Fertilizer name	Guaranteed ingredients (%)						Ingredients (%)				
	TN	P_2O_5	K_2O	MgO	MnO	B_2O_3	Ca	Fe	Cu	Zn	Mo
OAT 2	11.0 (NN)						16.4				
OAT 3	13.0 (NN)		46.0								

OAT 5	6.0 (AN)		9.0		2.00	2.00		5.7	0.04	0.08	0.043
OAT 6				16.0							
OAT 7	11.0 (AN)	61.0									

Note: TN: total nitrogen, AN: Ammonia nitrogen, NN: Nitrate nitrogen,

Table 2.2. The amount of OAT fertilizer used for experiment (g/1000 L)

Fertilizer name	Weight (g)
OAT 2	950
OAT 3	810
OAT 5	50
OAT 6	500
OAT 7	155

2.4. Tomato seedlings production and transplantation

Tomato seedlings preparation was conducted in plastic nursery house. Tomato seeds (*Solanum lycopersicum* L.) were sown into plastic trays containing holes (5 cm x 5 cm x 7 cm in length, width and depth) filled up with the germination medium. When tomato seedlings have 2 cotyledons, ½ concentration of liquid fertilizer was supplied to the bottom of tray to boost nutrient for seedlings and maintain the medium moisture.

Fig. 2.6. Plastic tray for seeds sowing

Tomato seedlings (5 true leaves, about 25 cm in height) were spit gently from germination medium, and the solid particles adhering to the root system were removed by carefully soaking into fresh water.

Seedlings were then moved to glass greenhouse and were transplanted into 4 cultivation beds (4 m in length, 0.2 m in depth, 0.35 m in up-width, and 0.25 m in bottom-width) containing cultivation medium. In the center-bottom of each bed, a tube (4 m in length and 10 cm in diameter) containing pores was established to enhance and supply aeration to cultivation medium. The distance between 2 adjacent tomato plants was about 30 cm with the density of 6 plants/m^2.

In first week after transplanting, tomato plants were irrigated only by fresh water. In subsequent 2 weeks, ½ concentration of liquid fertilizer were supplied, and after 3 weeks, full concentration of liquid fertilizer was supplied through dripped irrigation system.

CHAPTER 3

PREDICTION OF TOMATO MOMOTAROU HARUKA FLOWER-CLUSTERS OCCURRENCE USING CUMULATIVE HEAT UNIT AND CUMULATIVE SOLAR RADIATION

Abstract

The relationship between the occurrence of tomato flower-clusters and environmental factors in greenhouse cultivation was examined and the mathematical models for the duration of flower-clusters occurrence (DFO) were established. Tomato (*Solanum lycopersicum* L. Var. Culta. Momotarou Haruka) was cultivated by medium culture from September 2018 to May 2019. During cultivation, stem elongation speed gradually increased to 25.68 cm/week after 58 days of transplanting. DFO took 5 to 18 days, while cumulative heat unit (CHU) and cumulative solar radiation (CSR) ranged from 86.5 to 279.1 °C.day, and 31.6 to 230 MJ/m^2, respectively. There was a strong significant relationship between CHU and DFO ($r^2 = 0.93$, RMSE = 0.73). Multiple regression analyses for DFO using CHU and CSR as explanatory variables indicated the high accuracy of estimation ($r^2 = 0.94$, RMSE = 0.71).

3.1. Introduction

The growth of plants is largely influenced and defined by fluctuating and unstable environmental factors, thus predicting plant growth and yield throughout cultivation has become increasingly complex. More accurate predictions can be made if we possess quantitative information about the various relationships between plant growth and environmental conditions. So far, these relationships were examined using different equations (Overman and Scholtz, 2002; Christopher, 2006). Furthermore, various plant phenotype characteristics (e.g., elongation speed of stems, shape and area of leaves, coming and opening terms of flowers, maturation and ripening terms of fruits) are influenced by environmental conditions (e.g., temperature, humidity, light intensity, CO_2 concentration, wind velocity, absorption of water and fertilizer) (Caliskan *et al.*, 2009). These approaches can be applied to control plant cultivation systems under ideal growth conditions. Several studies have described mathematical models for tomato greenhouse cultivation, reporting weekly and seasonal predictions of fruit yield (Santos et al., 1992; Adams, 2002; Higashide, 2009; Wada *et al.*, 2013), simulation of tomato seedling growth under different temperature and solar radiation conditions (Gupta *et al.*, 2012), predicting fruit quality using various genetic, environmental, and management approaches (Génard and Lescourret, 2004; Yin and Struik, 2010; Martre *et al.*, 2011), and predicting plant growth and compositions of tomato fruits using water import rate (Bussières, 1994). However, less research has focused on modeling predictions for tomato flower-cluster occurrence with environmental factors.

A flower-cluster in a tomato plant can be defined as a group of buds that appear at a particular position on the stem and grows progressively from the bottom to the top of the stem, corresponding stem elongation (characteristics which are mainly genetically defined). After the occurrence of a flower-cluster, tomato fruit production is divided into several phases: flower bloom, pollination (in this study, all flowers were artificial pollinated as soon as buds on bud-cluster were opening), fruit cell division, maturity by cell enlargement, and ripening. But, in one plant, flower-clusters are stepwise occurring then growing phases of fruits between every cluster are different and also overlapping (for example, the occurrence time of bud-cluster 6 on this tomato plant might be the same as the occurrence of bud-cluster 5 on other plant). For understanding such plant growing conditions, durations of each phase on every cluster should be specified, but there are fewer methods to predict their base date and duration for every phase. Therefore, predicting the timing of flower-cluster occurrence is essential to fix the base date as the start of fruit growing, then if so, it can be used to estimate the elongation speed of individual tomato stems and to predict harvesting time on specific fruits cluster, as well as whose yield and productivity by maintaining ideal cultivation conditions in a glass greenhouse system.

To determine the optimum conditions for tomato cultivation, one must first consider temperature, particularly the concept of cumulative heat unit (CHU), which was defined as the amount of warmth accumulated in the plant during its growth (McMaster and Wilhelm, 1997; Gupta *et al.*, 2012; Miller *et al.*, 2018).

This index was widely applied to describe the timing of events in crop development and growth, particularly in crop simulation models (McMaster and Wilhelm, 1997, such as the determination of the duration of the crop growing season (Elnesr *et al.*, 2013), predicting the duration of plant stages, assessing the suitability of a region for the cultivation of a particular crop; estimating the time of harvest and crop yield (Perry et al., 1997), or defining the best timing of fertilizer application (Elnesr and Alazba, 2016; Ahmad *et al.*, 2017). However, using CHU has some limitations, as temperature varies greatly between daily low and high values (exhibiting a linear relationship with time), but some parameters of plant development are not linear (Bonhomme, 2000).

Solar radiation is also a key factor in influencing crop growth. During tomato cultivation, plant size and total biomass increase, while the amount of solar radiation remains constant, thus the concentration of photosynthetically active radiation per leaf area decreases. This means that light intensity is a limiting factor of plant growth, as photosynthetic efficiency is restricted by the intensity of solar radiation.

Cumulative solar radiation (CSR) is the total amount of photosynthetically active radiation over 24 hours, measured using the number of active photons. CSR strongly impacts photosynthesis and respiration through the leaves and showed a positive correlation with crop productivity and growth rate during cultivation (Faust et al., 2005). Previous studies have investigated the effects of CSR, for instance, the dark respiration rate and the gross photosynthesis capacity of tomato plants are known to decrease as leaves age (Xu et al., 1997), CSR perceived from anthesis to harvest influenced the total yield of single-truss tomatoes (McAvoy et al., 1989), and CSR could predict weekly tomato yield in a commercial greenhouse (Higashide, 2009).

Previous literature has shown that CHU and CSR are important environmental factors influencing tomato growth and yield, but their interactive effect has not been investigated. Therefore, in this study, the relationship between duration of flower cluster occurrence (DFO), CHU, and CSR were investigated, and mathematical models were developed from simple, polynomial and multiple regressions approach. Such kinds of trials are the first study to fix the base date for every fruit clusters that can be adopted to specify the terms of tomato growing phases, like blooming of flowers, maturation and ripening of fruits, and to provide important information of yield predictions from every flower clusters.

In latest greenhouse cultivation, temperature is controlled by the warming equipment and ventilation system. In the case of solar radiation, past ambient intensity can be acquired from the records of meteorological observation. It means, after the first cluster occurrence, DFO will be able to predict using the set value of temperature to the warming equipment and ambient CSR. Therefore, the achievements of this research will also make significant contribution to optimize environmental condition in the greenhouse for tomato cultivation.

3.2. Materials and Methods

Tomato cultivation was performed from November 2018 to May 2019 in a glass greenhouse, with a floor area of 66.5 m^2 (9.1 m L × 7.3 m W; 4.5 m H) covered by the glass with a stainless-steel frame at the Faculty of Agriculture, Saga University, Japan. A retention warming heater was operated to maintain the air temperature over 15 °C from November 2018 to March 2019, adequate ventilation was insured by fans, and sliding windows were opened when the ambient temperature exceeded 30 °C. Fluorescent lights were switched on from 5 to 7 pm daily.

The variety of tomato used for this experiment was *Solanum lycopersicum* L. Var. Culta. Momotaro Haruka (Takii & Co., Ltd., Japan), a popular indeterminate-inflorescence variety developed in Japan. The mature fruits of this variety weigh about 220 g and are commonly consumed fresh. Tomato seeds were sowed in a plastic nursery house on 25 September 2018 and a total of 48 seedlings after the coming of the first flower-clusters (plant height ~ 20 cm) were transplanted on 1 November 2018 to the solution cultivation system containing a commercial porous solid medium (Isolite CG, Isolite Insulating Products Co., Ltd., Japan), which was produced by baking diatomaceous earth (<0.6 kg/litter; particle size 4 mm; water absorption rate 70/100 g; pH 6; and chemical composition 80 % SiO_2, 12 % Al_2O_3, 6 % Fe_2O_3). The dimensions of the cultivation bed were 4 × 0.33 × 0.2 m; a total of four beds were used in this study. The interval between each plant was 30 cm with a density of 6 plants/m^2. Stem height was maintained at a maximum of 2 m by hanging culture. The nutrient medium was prepared by a balanced medium prescription using commercial fertilizer (OAT Agrio Co., Ltd., Japan) with 20 mg/L nitric nitrogen, 210 mg/L ammonic nitrogen, 93 mg/L P_2O_5, 377 mg/L K_2O, and 219 mg/L CaO, 80 mg/L MgO, 1 mg/L MnO, 1 mg/L B_2O_3, 2.9 mg/L Fe, and other micro-elements. The nutrient solution was provided to the plants through micro-irrigation tubes controlled by a timer.

Temperature and solar radiation were monitored using illuminance recorders (RTR-574, T&D Co. Ltd.). These were set at the tomato apexes about 2 m from the surface on the cultivation bed and the middle of the canopy (about 1 m height) during cultivation. The CO_2 concentration was monitored by CO_2 recorders (RTR-576, T&D Co. Ltd.) in 10-min intervals. The flower-clusters of each plant were numbered in order of their occurrence (bottom to top) and their duration (days) were recorded from the moment they first appeared. A solution of 4-chlorophenoxy-acetic acid was applied to support the pollination of tomato flowers. Changes in stem length were measured weekly.

CHU and CSR were calculated following equations (3.1) and (3.2).

$$CHU_i = \sum_{i=1}^{n} \left(\frac{T_{max}+T_{min}}{2} - T_{base} \right)_i \qquad (3.1)$$

$$CSR_i = \sum_{i=1}^{n} S_i \qquad (3.2)$$

where, CHU_i is the cumulative heat unit on ith day (^{O}C.day); n is the specific period of plant growth (days); T_{max} and T_{min} are the maximum and minimum temperature recorded in a particular day; T_{base} is the base temperature at which the tomato plants were supposed to stop growing, set as 6.1 °C according to information from previous studies (Adams *et al.*, 2001; Bouzo *et al.*, 2014); CSR_i is the cumulative solar radiation on i^{th} day (MJ/m^2); and S_i is the solar radiation on i^{th} day.

The correlations between the duration of flower-clusters occurrence (DFO), CHU, and CSR were estimated via simple, multiple, and polynomial regressions, represented in the following equations:

$$y_i = \alpha + \beta x_i + \varepsilon_i \, ; \qquad (3.3)$$

$$y_i = \alpha + \beta_1 x_{1i} + \beta_2 x_{2i} + \varepsilon_i \, ; \qquad (3.4)$$

$$y_i = \alpha + \beta_1 x_i + \beta_2 x_i^2 + \beta_3 x_i^3 + \ldots + \beta_n x_i^n + \varepsilon_i \qquad (3.3)$$

where y_i is the day of occurrence of i^{th} flower-clusters as a response variable (dependent factor); α and β are the intercept and slope coefficients (regression coefficients); ε_i is the residuals of models; x_i (in the equation 3.3.) is the i^{th} CHU or i^{th} CSR calculated in the corresponding i^{th} flower-clusters (predictor variables or independent factors) in simple and polynomial regression models; and x_{1i} and x_{2i} (in the equations 3.3 and 3.4) are CHU and CSR respectively in multiple and polynomial regressions models. The regression coefficients α and β were estimated from observed data using the least-squares method.

Calculation results and the accuracy of mathematical models were checked by comparing the adjusted R-squared and predicted R-squared calculated by full cross-validation using R 4.02 (R Core Team, 2020) with the *caret* package (Kuhn, 2020).

3.3. Results and Discussion

3.3.1. Environmental conditions for tomato cultivation

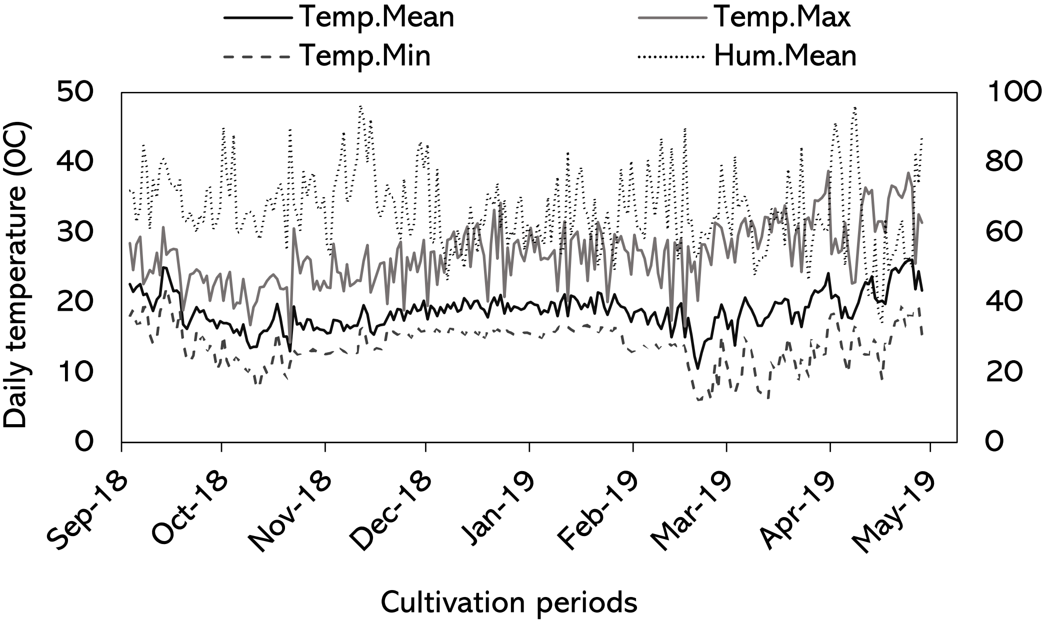

Fig. 3.1. Daily mean, maximum, minimum air temperatures, and relative humidity in the glass greenhouse

Fig. 3.1 shows the variations in environmental conditions as air temperature of daily mean, maximum, and minimum and relative humidity (RH) in the glass greenhouse during cultivation. Daily mean air temperature decreased from 22.5 °C in September to 12.5 °C in the middle of November 2018, then the warming heater (set at 15 °C) was run until the mid-March 2019, after which the temperature was gradually increased until the end of May 2019 to 23 °C. Large daily temperature variations were recorded, ranging between

18.1 °C in September to November to 18.5 °C in November to February, and around 20 °C in March. Relative humidity fluctuated widely throughout the cultivation period, ranging between 35 and 96%.

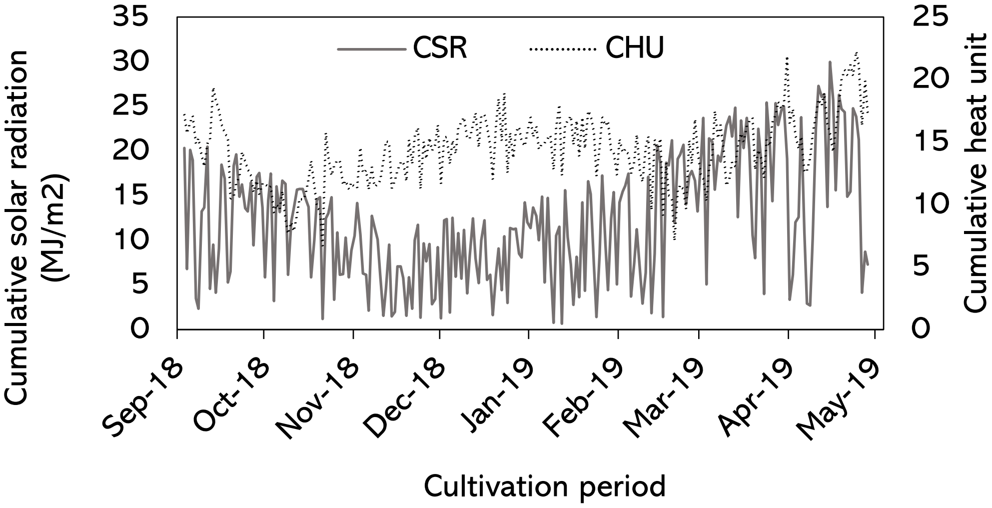

Fig. 3.2. Daily fluctuations in heat unit and solar radiation during tomato cultivation

Fig. 3.2 shows the fluctuations of daily heat unit and solar radiation throughout the tomato plant cultivation period. Solar radiation tended to decrease from September to the middle of December 2018, despite wide fluctuations, then gradually increased until the end of May 2019, corresponding to the duration of sunshine. Meanwhile, the daily heat unit decreased from September (after transplanting) until the end of October 2018, then fluctuated as a parabolic curve with a peak in January and declining until mid-March 2019, and finally increased gradually until the end of May 2019. The heater in the greenhouse operated from November to mid-March to maintain an ambient temperature of > 15 °C. The daily heat unit during this period is represented by a parabolic curve.

3.3.2. Stem elongation and flower-cluster occurrence

Fig. 3.3 shows the weekly average elongation speed of tomato stem length (ESS). They increased gradually and reached 25.68 cm at the end of December, 42 days after the first measurements on 16th November, then gently decreased to 10 cm/week until the end of March 2019. The trend in ESS is graphically represented as an inverse curve toward CSR change.

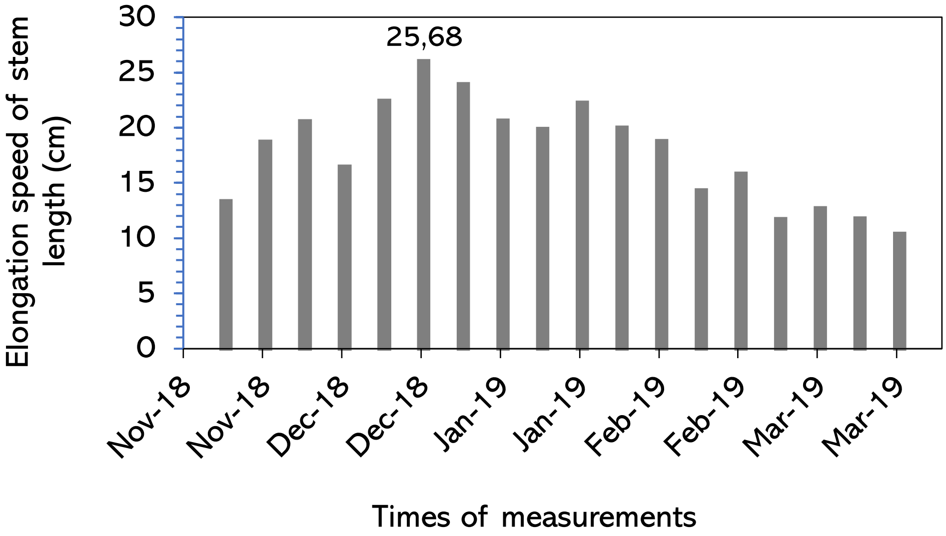

Fig. 3.3. Weekly elongation speed of stem length (ESS) during tomato cultivation

Fig. 3.4 indicated the date of flower-cluster occurrence observed in our study. We started recording the occurrence of flower-clusters from the second cluster (C2) as the first flower-clusters. The first cluster were already present when seedlings were transplanted to the cultivation system. The emergence of C2 may have taken longer due to the effect of transplanting and the time required for seedlings to adapt to the medium hydroponic system. ANOVA results show a significant difference in the emergence time of two adjacent flower-clusters on tomato plants (n = 205, F_{value} = 174.06, p-value < 0.001). C2, C8, and C12 took the longest to emerge, at 16.7 days, 11.68, and 12.4 days, respectively, while the others (C3, 4, 5, 6, 7, 9, 10 and 11) emerged after 7–9 days. Furthermore, there were four groups by differences in occurrence time by Tukey HSD, the first group including C2, 4, 8, and 12, the second C3, 6, 7, and 10, the third C5 and 11, the fourth C9.

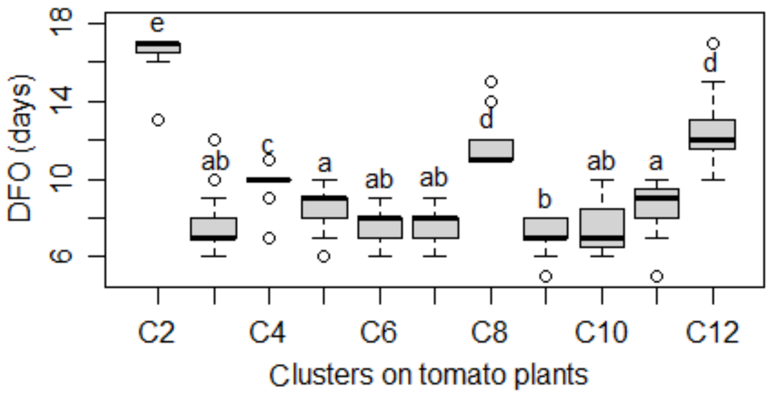

Fig. 3.4. Plot of the duration of flower-clusters occurrence (DFO) as analyzed by the Tukey HSD test

Fig. 3.5 highlights the relationship between DFO, CHU(A), and CSR(B), respectively. The DFO of tomato were strongly affected by CHU (r^2 = 0.93), and CSR (r^2 = 0.83). From Fig. 3.2, we can see that CSR is regularly changing by seasonal variation in day length; yet CHU values show considerable fluctuations up and down due to the heater operation, but the correlation coefficient of CHU became higher than CSR.

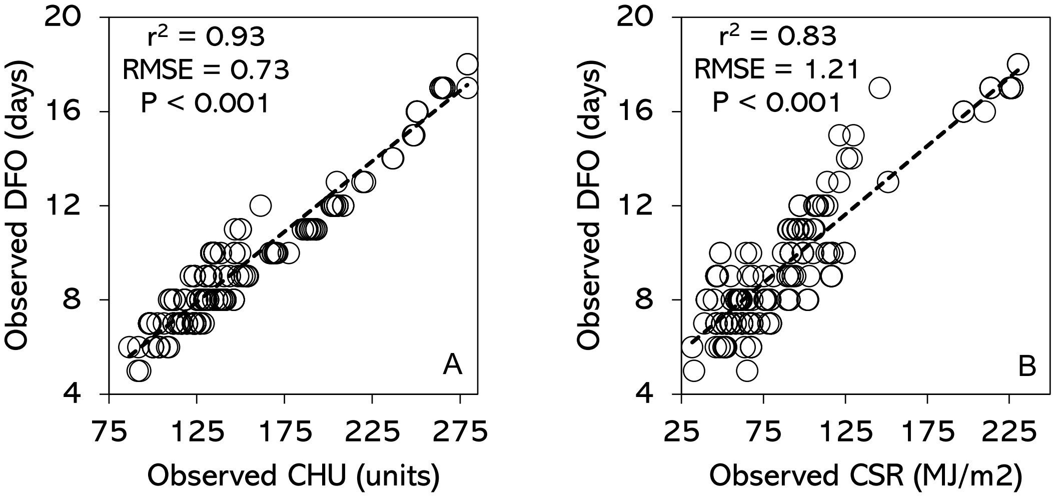

Fig. 3.5. Relationship between DFO and CHU(A), CSR(B)

The correlation coefficients between ESS and CHU was 0.69 and that of ESS and CSR was −0.52, respectively. From these relationships, we conclude that DFO was likely controlled by CHU.

3.3.3. Mathematical models for the occurrence of flower-clusters

Table 3.1 displays the results of our descriptive statistical analysis of data applied for mathematical models. There were 205 observations of DFO, CHU, and CSR. The flower-clusters occurred between 5 and 18 days, the CHU ranged from 86 to 279 ^{0}C.day, and the CSR fluctuated from 31 MJ/m^2 to 230 MJ/m^2.

Table 3.1. The general information on variables used for mathematical models

Parameters	n	Min.	Max.	Avg.	SD*
DFO (days)	205	5	18	9.6	3.05
CHU (^{0}C.day)	205	86.6	279.1	153.8	49.13
CSR (MJ/m^2)	205	31.6	230.4	90.7	47.81

n: number of samples, SD: standard deviation

Table 3.2 showed the mathematical models established by simple, polynomial, and multiple regressions in the occurrence of flower-clusters (response variable) against CHU and CSR (predictor variables). In models from 1 to 7 using only CHU were indicated significant relationships between all predictor variables in models at significant level $P < 0.05$, 0.01, and 0.001. Range of adj.R^2 and pred.R^2 for models 1 to 7 were indicated from 0.91 to 0.94, and models from 2 to 7 became the same values between adj.R^2 and pred.R^2. Therefore, these models were unlikely to be over-fitted. RMSE of models 1 to 7 were from 0.73 to 0.89, which were less than one day. It means these models could predict DFO within the error of less than one day. Then we judged the accuracy of estimation on our model could reach the level of practical prediction.

Table 3.2. Results of simple, polynomial, and multiple regressions for DFO using CHU and CSR

Model	Equations	adj.R^2	pred.R^2	RMSE	EI	RPD
1	$y = 0.434^{*} + 0.0598\,x_1^{***}$	0.93	0.92	0.80	12.3%	3.8
2	$y = 5.358^{***} + 1.641\times10^{-4}x_1^{2***}$	0.93	0.93	0.78	12.0%	3.9
3	$y = 6.934^{***} + 5.539\times10^{-7}x_1^{3***}$	0.91	0.91	0.89	13.7%	3.4
4	$y = 3.437^{***} + 0.0231x_1^{**} + 0.0001x_1^{2***}$	0.93	0.93	0.77	11.8%	4.0
5	$y = 2.659^{***} + 3.899\times10^{-2}x_1^{***} + 2.007\times10^{-7}x_1^{3***}$	0.93	0.93	0.76	11.7%	4.0
6	$y = 4.881^{***} + 2.154\times10^{-4}x_1^{2***} + 1.761\times10^{-7}x_1^{3*}$	0.93	0.93	0.77	11.8%	4.0
7	$y = -5.595^{*} + 0.1915\,x_1^{***} - 8.884\times10^{-4}x_1^{2***} + 1.830\times10^{-6}x_1^{3\,***}$	0.94	0.94	0.73	11.2%	4.2
8	$y = 4.365^{***} + 0.058\,x_2^{***}$	0.83	0.82	1.25	19.2%	2.4
9	$y = 7.410^{***} + 2.119\times10^{-4}x_2^{2***}$	0.78	0.78	1.41	21.7%	2.2
10	$y = 8.298^{***} + 8.652\times10^{-7}\,x_2^{3***}$	0.71	0.70	1.64	25.2%	1.9
11	$y = 4.161^{***} + 6.216\times10^{-2}x_2^{***} + 1.555\times10^{-5}x_2^{2\,\mathrm{ns}}$	0.83	0.82	1.26	19.4%	2.4
12	$y = 4.106^{***} + 6.216\times10^{-2}x_2^{***} - 6.964\times10^{-8}\,x_2^{3\,\mathrm{ns}}$	0.83	0.82	1.25	19.2%	2.4
13	$y = 5.980^{***} + 5.886\times10^{-4}x_2^{2***} - 1.635\times10^{-6}x_2^{3***}$	0.84	0.83	1.22	18.8%	2.5
14	$y = 8.759^{***} - 8.767\times10^{-2}x_2^{*} + 1.385\times10^{-3}x_2^{2***} - 3.698\times10^{-6}x_2^{3***}$	0.84	0.83	1.20	18.5%	2.5
15	$y = 1.1367^{***} + 0.0454\,x_1^{***} + 0.0166\,x_2^{***}$	0.94	0.94	0.71	10.9%	4.3

Notes: x_1 and x_2 are CHU and CSR respectively, y is the duration of flower-clusters occurrence (DFO); *, **, and *** significant at $P < 0.05$, 0.01, and 0.001; $^{\mathrm{ns}}$ not significant; adj.R^2 and pred.R^2 are adjusted and predicted R-squares respectively; RMSE is the root mean squared error of the prediction. EI: evaluation index, RPD: ratio of standard deviation of reference data in prediction sample to SEP.

Model 1 showed a simple linear regression, with a pred.R2 of 0.92 and RMSE of 0.80, suggesting that DFO on tomato plants increased significantly with a rise in CHU and that 93% of the variation in DFO could be explained by changes in CHU alone. Model 7 had the highest pred.R2 (0.94) and the smallest RMSE (0.73) of the seven models; it is represented by the following equation:

$$y = -5.595 + 0.1915x_1 - 8.884\times10^{-4}x_1^2 + 1.830\times10^{-6}x_1^3$$

where y is DFO and x_1 is CHU.

Models 8 to 14 showed the results of regressions for DFO using CSR. While models 11 and 12 were not significant, others were significant at the $P < 0.05$, 0.01, and 0.001 level.

Model 8 shows that DFO and CSR had a strong significant relationship (pred.R^2 = 0.82 and RMSE = 1.25), with 83% of the variation in DFO explained by changes in CSR. These findings suggest that CHU had a stronger relationship with DFO than with CSR.

Model 14 had the highest pred.R^2 (0.83) and smallest RMSE (1.20); it could be represented using the following equation:

$$y = 8.759 - 8.767\times10^{-2}x_2 + 1.385\times10^{-3}x_2^2 - 3.698\times10^{-6}x_2^3$$

where y is DFO and x_2 is CSR.

Lastly, model 15 shows the multiple regression for DFO with both CHU and CSR, with the highest pred. R^2 value of all examined models (0.94) ($P < 0.001$) and an RMSE of 0.71, described using the following equation:

$$y = 1.1367 + 0.0454x_1 + 0.0166x_2$$

where x_1 and x_2 are CHU and CSR, respectively.

Fig. 3.6 illustrates the prediction result based on model 15. Both factors had a beneficial impact on DFO (i.e., an increase in temperature and solar radiation had significant positive effects on DFO). Furthermore, CHU and CSR explained about 94% of the variation in DFO.

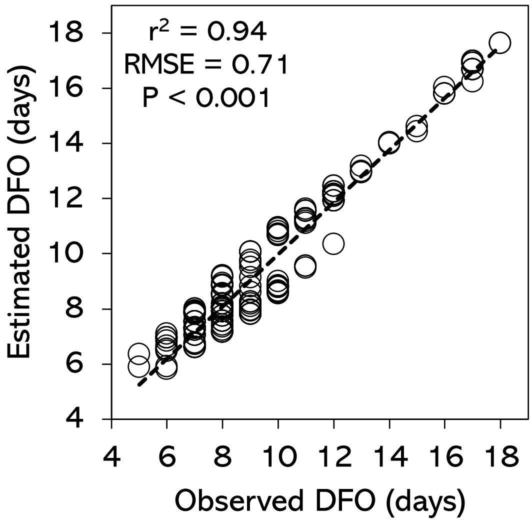

Fig. 3.6. Result of prediction by MLR using CHU and CSR as in model 15

Therefore, mathematical models established from polynomial and multiple regression suggest that CHU and CSR could be potential indices to predict the occurrence of flower-clusters. There were moderate and high significant relationships between CHU or/and CSR and DFO whose coefficients of determination ranged from 0.71 to 0.94 ($P < 0.001$).

In greenhouse cultivation, relationship between CHU and CSR indicated as $r^2 = 0.632$, p-value < 0.001. Therefore, between explanatory variables in the multiple regression model had the potential of collinearity. For checking the effect of collinearity, the variance inflation factor (VIF) score on an explanatory variable between CHU and CSR in the multiple regression was examined (James, *et al.*, 2013; Kassambara, 2018). If VIF indicates from 5 to 10, there is a certain potential of critical collinearity. If VIF ranges from 1 to 5, there is a moderate correlation between explanatory variables but not severe enough to warrant accurate estimation, thus practically acceptable level (Frost, 2019; O'brien, 2007). VIF between CHU and CSR for model 15 in Table 3.2 was calculated as 4.73, which ranged with acceptable levels. In addition, this model by CHU and CSR presented higher accuracy for the prediction than each model by CHU or CSR. It indicated that residual in separately using CHU or CSR might be utilized for prediction by combining CHU and CSR.

Evaluation Index (EI) is one of the criteria to judge the accuracy of prediction for multivariate analysis, which are estimated as the ratio between RMSE and the range of samples (Mizuno et. al., 1988). EI specifies 4 classes of accuracy: very high as 0 to 12.4%, high as 12.5 to 24.9%, slightly high as 25.0 to 37.4%, low as 37.5 to 49.9%. In table 2, the EI of models 1 to 7 and 15 except for model 3 was less than 12.4%, therefore it was estimated as "very high”, model 8 to 14 except for 10 as “high”. The other criteria, RPD is well known for non-destructive evaluation, which is calculated as the ratio between RMSE and SD of the original population (Williams and Sobering, 1993). RPD indicates 3 classes of practical application: the same accuracy level of chemical analysis as more than 8.0, quality control as 5.0 to 7.9, screening as 3.1 to 4.9, roughly screening as 2.5 to 3.0. RPD of models 1 to 7 and 15 except for model 3 were classified among screening. Thus, these models were judged as the same accuracy as the screening level. Theoretically, RMSE might be improved by adding more predictor variables (in this study, we used CHU and CSR) or stabilized by increasing numbers of samples, e.g. integrating several year’s cultivation data.

In greenhouse cultivation, environmental factors such as temperature, radiation intensity, humidity are easily monitored but fluctuate significantly. Therefore, simply monitoring these variables is not indicative enough to understand or accurately predict plant physiological responses. However, this study demonstrated cumulative indices of CHU and CSR had practical accuracy to predict DFO using mathematical models. Therefore, greenhouse growers could use these models to predict the DFO and thus take appropriate measures to minimize the adverse impacts of large fluctuations in environmental conditions and market demand. DFO also had the potential to be applied the method to specify the base date of plant growing phase, like flower bloom, pollination, fruit cell division, maturity by cell enlargement, and ripening and yields for every flower clusters. Moreover, if temperature and light intensity in greenhouse cultivation are strictly and well-controlled, plant growth phases including DFO, as well as fruit maturation and yield will be estimated more accurately.

3.4. Conclusions

CHU and CSR are both common indices used to describe the growing capacity and the yield of tomatoes. However, few studies have used those indices to predict the occurrence of flower-clusters. In this study, Momotaro Haruka varieties were expressed indeterminate characteristics. Our findings showed that CHU and CSR have a significant impact on the occurrence of flower-clusters and can be used in mathematical modeling to predict this phenotypic properly of plant growth with $r^2 = 0.94$ ($P < 0.001$) and an RMSE of 0.71. By using this model, DFO will be concreated as the base date of the plant growth phase and will contribute to clarify in-detailed plant growth phases. Further research could focus on the impact of temperature and solar radiation on the stem elongation capacity of tomato plants to clarify the relationships between those environmental factors, growth rate, and the occurrence of flower-clusters.

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CHAPTER 4

RELATIONSHIPS BETWEEN TOMATO CLUSTER GROWTH INDICES AND CUMULATIVE ENVIRONMENTAL FACTORS DURING GREENHOUSE CULTIVATION

Abstract

Despite of growth characteristics of plants are mainly defined by genetic information, however, they are also affected by environmental factors, such as air temperature, solar radiation, and humidity. There is a strong potential and demand to predict plant growth by environmental factors. Therefore, this study established mathematical models via multiple linear regression analysis (MLR) to describe the relationship between tomato cluster's growth indices and environmental factors in greenhouse cultivation. The Japanese tomato variety (*Solanum lycopersicum* L. Var. Culta. Momotarou Haruka) was cultivated in a hydroponic culture system using a porous solid medium from September 2019 to June 2020 in a glass greenhouse. The significant correlations among growth indices and environmental factors showed that the cumulative solar radiation (CSR) had a stronger effect on the number of flowers (NFl) rather than the cumulative heat unit (CHU) and vapor pressure deficit (VPD). Meanwhile, the number of fruits (NFr) relied much on VPD than CHU and CSR. Also, pollination condition was sensitive to VPD; NFr and enlargement of fruit cells during fruit maturation might be important factors in fruit-cluster weight (CWt). Mathematical models via MLR of cumulative environmental factors, such as CHU, CSR, and VPD

could explain tomato cluster's growth indices, such as NFl, NFr, fruit perimeter (PFr), CWt, and duration of tomato clusters with the coefficient of determination (R^2) ranging from 0.742 in the fruit maturation duration (FM) model to 0.953 in the PFr model. In MLR models, CHU was the most important factor in the duration of tomato clusters and PFr with the relative importance metrics (RIM) of ranging 29.47%–43.66%; CSR for NFl with RIM was 36.83%; and VPD for NFr and CWt with RIM were 37.37% and 29.37%, respectively. By MLR analysis, results showed the potential of using CHU, CSR, and VPD to describe and predict the growth indices of tomato clusters by mathematical models.

4.1. Introduction

A group of buds occurs on a tomato stem is call a bud-cluster. It becomes flowers called flower-cluster. Fruits come after these flowers are pollinated, which are called a fruit- or tomato cluster. The term, tomato cluster growth, can be divided into periods, such as the duration from buds' cluster occurring to the opening of buds (OB), from well-pollinated flowers to fruit maturation (FM), and from fruit ripening to harvest (FR). During these stages, cell division and enlargement, accumulation and storage of polysaccharides, and the number of flowers on each flower-cluster are controlled genetically (Ariizumi et al., 2013; Azzi et al., 2015; Gonzalo et al., 2020). However, in a specific study, we used one variety of tomato that having the same genetic system, and they have the same reaction and expression, hence, the other concerns as impacts of environmental factors like temperature, solar radiation, and humidity on development during cultivation are crucial important (Adams et al., 2001; Driss et al., 1995; Uzun, 2007), especially, the fruits number and size and fruit-cluster's weight. Tomato clusters are continuously and regularly produced on the stems; thus, the growth stages between every cluster overlap, and these growth conditions are gradually dissimilar. Therefore, to presently comprehend tomato growth conditions, precise estimation for every tomato cluster is essentially required.

Temperature, light intensity, and humidity are principal environmental factors that crucially control tomato growth (Shamshiri et al., 2018). Also, the cumulative heat unit (CHU)—the amount of warmth accumulated in the plant during its growth, cumulative solar radiation (CSR)—the total amount of photosynthetically active radiation over a day, and vapor pressure deficit (VPD)—the difference between the amount of moisture in the air and the quantity it can hold when saturated—are well-known secondary indices retrieved from those environmental factors and extensively applied in crop sciences. For instance, CHU was used to estimate and describe the growth stages of crops (Anandhi 2016; Elnesr and Alazba, 2016; Miller et al., 2018; Uzun, 2007), predict the best timing of fertilizer application (Rens et al., 2016), and plan sowing and transplanting dates to produce separately desired harvest periods and yields (Machado et al., 2004; Pathak and Stoddard, 2018; Worthington and Hutchinson, 2006); CSR and VPD were used to assess the regulation of photosynthesis and transpiration, evaluate tomato growth, and its yield during cultivation (Driss et al., 1995; Higashide, 2009; Jiao et al., 2019; Leonardi et al., 2000; Lu et al., 2015). However, there were no studies regarding the environmental factors to describe and predict the development duration and growth indices of tomato clusters to our knowledge.

Here, we investigated the relationships between CHU, CSR, and VPD and each duration of tomato cluster development, such as OB, FM, and FR, the number of flowers (NFl), number of fruits (NFr), fruit perimeter (PFr), and the fruit-cluster weight (CWt) using mathematical models established from multiple linear regression (MLR) analysis. The effects of environmental factors on every tomato cluster are not homogeneous. The number of flowers translated into fruits is not often equal, and cell division and enlargements during maturation would also be different. As a result, examining the development conditions for each tomato cluster becomes more difficult, but there are fewer methods to predict it. Therefore, establishing mathematical models to describe those growth indices are practical methods for predicting the growth status of a tomato cluster, and then estimating the harvest time of individual fruit-cluster, as well as the lengthening production period and total yield of a plant by maintaining ideal cultivation conditions in a glass greenhouse system.

CHU, CSR, and VPD are indices easy to integrate and calculate from temperature, solar radiation, and relative humidity data during greenhouse cultivation using convenient monitoring devices, hence, mathematical models using those indices have the potential and practical feasibility for monitoring, estimating, and predicting tomato production. In this study, a modification for CHU calculation was also applied and examined using MLR to compensate for its original limitation, which was derived only from the mean daily temperature above the base temperature.

4.2. Materials and methods

4.2.1. Greenhouse facility and cultivation medium

Tomato cultivation was conducted in the glass greenhouse, which had 66.5 m^2 of floor area (9.1 × 7.3 × 4.5 m) in the Faculty of Agriculture, Saga University, Japan, from September 2019 to June 2020. For growth conditions control, a warm-air heater was operated during winter to maintain the air temperature above 15°C, a set of five fans were applied and sliding windows were used to enhance the ventilation capacity when the glass greenhouse temperature exceeded 25°C. Artificial fluorescent lamps were switched on daily (17:00–19:00). Carbon dioxide was automatically maintained (at 450–500 ppm) using pure CO_2 tanks connected to a monitoring system.

The porous solid medium (Isolite CG, Isolite Insulating Products Co., Ltd., Japan) was prepared in four cultivation beds (4 × 0.33 × 0.25 m). The nutrient medium was prepared from a commercial fertilizer (OAT Agrio Co., Ltd., Japan) containing macro-elements, such as 105-mg/L nitric nitrogen, 10-mg/L ammonic nitrogen, 46-mg/L P_2O_5, 190-mg/L K_2O, and 110-mg/L CaO, and other micro-elements. The nutrient solution was supplied to the seedlings through micro-irrigation tubes controlled by a timer (H5L, OMRON Corporation, Japan).

4.2.2. Tomato seedling preparation

The tomato seeds (*Solanum lycopersicum* L. Var. Culta. Momotarou Haruka) (Takii & Co., Ltd., Japan) was sown in a plastic nursery on 19th September 2019. Forty-eight seedlings with a certain number of leaves (approximately six true leaves), suitable plant height (approximately 20 cm), and the evolution of the first flower-cluster were transplanted into the glass greenhouse on 1st November 2019 with an interval of 30 cm and density of six plants.m^{-2}. Tomato stems' height was maintained at a maximum of 2 m from the ground by plastic strings (hanging culture type).

4.2.3. Observations

Temperature and solar radiation were monitored every 10 min using an Illuminance Recorder (RTR-574, T&D Co. Ltd., Japan). Their positions were set at the tomato apexes (2 m from the surface of the cultivation bed) and the middle of the canopy (1 m during cultivation).

For each tomato plant, tomato clusters were numbered according to their occurrence on stems from bottom to top. The date when a bud-cluster occurs on the tomato stem, bud opening, the start of fruit ripening (when the fruit perimeter no longer increases, and its dark green exocarp becomes lighter), and harvesting (when all the fruit exocarp is red) were recorded. The number of flowers and their translation to fruits on each cluster were counted. Fruits were harvested using the color chart when fruits turned into light-red. The perimeter was measured as the surrounding of each fruit. The fruit-cluster's weight was calculated by summing all fruit weights on the corresponding tomato cluster. Fruit yield was estimated per plant every two weeks.

4.2.4. Calculation and establishment of mathematical models

The initial heat unit concept is defined by taking the average minimum and maximum temperatures in a day. It assumes that the correlation between temperature and growth duration is linear (Ahmad et al., 2017). However, it does not consider the fluctuation and variation of daytime temperature affected by the day-length and number of sunshine hours on a particular day. Therefore, in this study, we modify the heat unit calculation, as shown in formula (1). CHU and CSR were calculated as follows in equations 4.1 and 4.2.

$$CHU_i = \sum_{i=1}^{n} DL_i \times SS_i \times \left(\frac{T_{max}+T_{min}}{2} - T_{base}\right)_i \qquad (4.1)$$

$$CSR_i = \sum_{i=1}^{n} S_i \qquad (4.2)$$

Where;

CHU_i is the cumulative heat unit (units) until the *ith* day; n is the specific period of plant growth (days); T_{max} and T_{min} are the maximum and minimum temperatures recorded in a day; T_{base} is the base temperature where the tomato plant should stop growing, T_{base} is set at 6.1°C, according to the study (Bouzo and Favaro, 2014; Masle et al., 2006); CSR_i is the cumulative solar radiation

($MJ.m^{-2}$) and S_i is the solar radiation on the *ith* day. DL is the duration of daytime length (hours) of Saga Prefecture, calculated from sunrise to sunset via the geosphere-package in R (Hijmans, 2019). SS is the number of actual sunshine hours in a day, it is set equal to one on a rainy and cloudy day or if the number of sunshine hours is less than one.

Mathematical models for predicting NFI, NFr, PFr, CWt, and duration of OB, FM, and FR against CHU, CSR, and VPD were established using MLR analysis performed by R v.4.03 (R Core Team, 2020), which is represented in the following equation:

$$y_i = \alpha + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \varepsilon_i; \qquad (4.3)$$

Where;

y_i (response variable) is the growth index of tomato clusters as NFI, NFr, PFr, CWt, and duration of OB, FM, and FR; α and β are intercepts and slope regression coefficients, respectively; ε_i is the residual of models; x_{1i} , x_{2i} , x_{3i} are the *ith* CHU, CSR, and VPD calculated in the corresponding *ith* response variables. The regression coefficients, α and β, were estimated from observed data using the least-squares method.

The overfitting of models was checked by comparing the R^2 and the predicted R^2 calculated by full cross-validation analysis. The collinearity between the predictor variables, CHU, CSR, and VPD, in the MLR models was examined through variation inflation factor calculated using car-package (John and Sanford, 2019). The prediction models' accuracy was estimated via the root mean square error (RMSE) and the prediction error rate (PER), which were retrieved from repeated k-fold cross validation analysis performed using the caret-package (Max, 2020). The relative importance metrics (RIM) of predictor variables in MLR were calculated using the relaimpo-package (Ulrike, 2006).

4.3. Results and Discussions

4.3.1. Environmental conditions during tomato growth

Fig.4.1 presents the variations in environmental conditions of daily maximum, minimum, mean air temperatures, and VPD in the glass greenhouse during cultivation. Daily mean air temperature tended to decrease from 21.5°C in October 2019 to 16.5°C in January and February 2020; then it gradually increased to 23.5°C at the end of May 2020. There were significant daily temperature variations recorded, fluctuating around 16°C in October and November 2019, 7.5°C–10.5°C in December 2019 to March 2020, and approximately 11.2°C–14.5°C in April and May 2020. The daily mean VPD fluctuated around 0.177 and 2.115 kPa throughout cultivation and increased later during cultivation, while the discrepancy between nighttime and daytime VPD was 1.722–2.648 kPa in October and November 2019, 0.987–1.807 kPa from December 2019 to March 2020, and 2.236–2.905 kPa in April and May 2020.

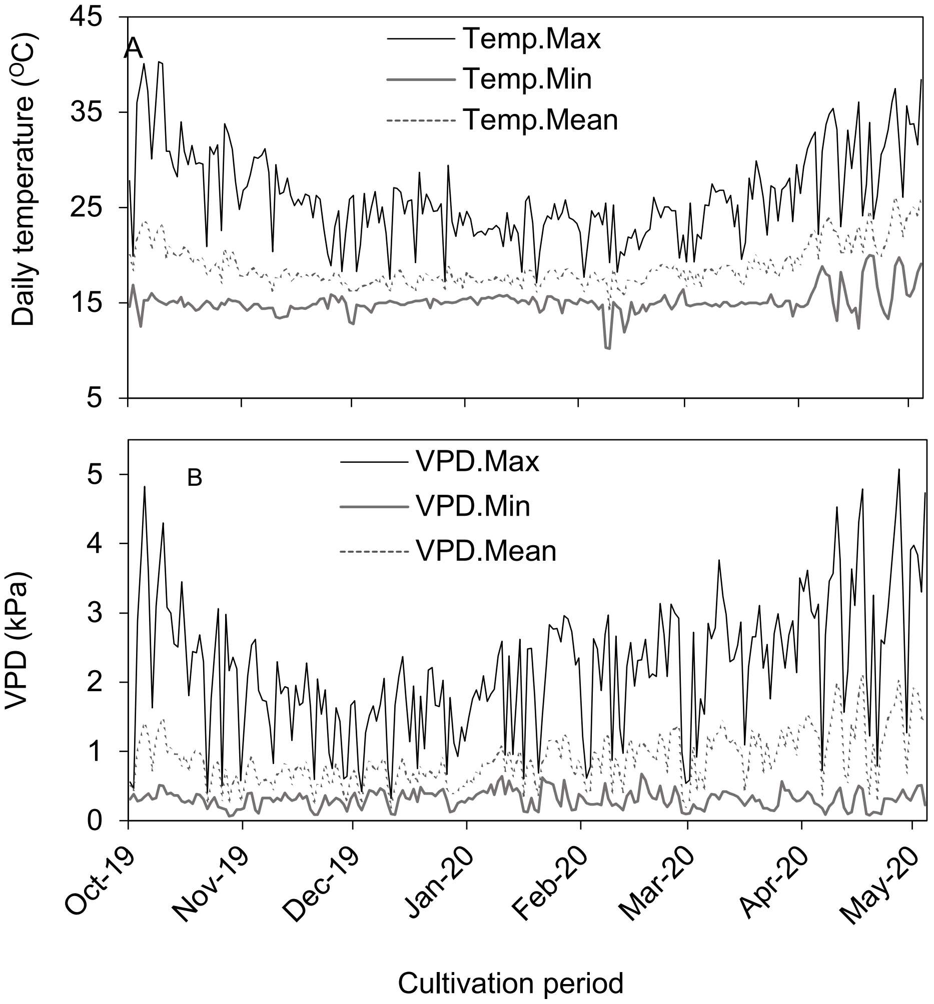

Fig. 4.1. Daily maximum, minimum, mean of air temperatures (A), and mean vapor pressure deficit (B) in the glass greenhouse during cultivation

Fig. 4.2 shows the daily fluctuations of heat unit (HU) and solar radiation (SR) throughout the tomato cultivation period. HU gradually decreased from 1400 units.day^{-1} in October 2019 to 600 units.day^{-1} in January 2020, then widely fluctuated and increased to 2350 units.day^{-1} in the middle of June 2020. Similarly, SR slightly decreased from October (approximately 11.2 MJ.m^{-2}.day^{-1}) to the end of December 2019 (approximately 9.0 MJ.m^{-2}.day^{-1}), then increased until the end of the cultivation (approximately 23.5 MJ.m^{-2}.day^{-1}) corresponding to the sunshine duration. It can be seen that HU had the same tendency variations with the fluctuation in SR ($r = 0.924$, $P < 0.001$).

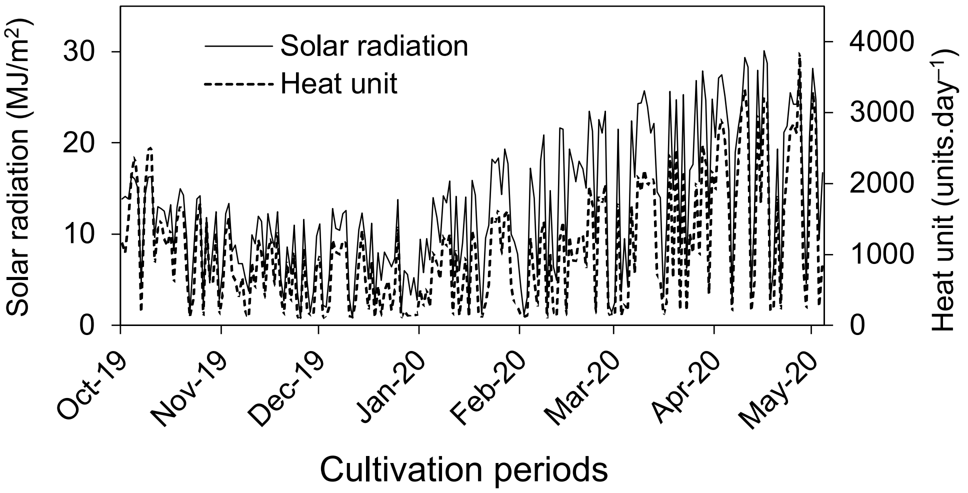

Fig. 4.2. Daily fluctuations in HU and SR during tomato cultivation in the glass greenhouse

4.3.2. Development of tomato clusters

Fig. 4.3 presents the average number of flowers on each fruit-cluster (C) of tomato plants that fluctuated from 3.5 (C14) to 5.9 (C1). Meanwhile, the average NFr per cluster was 2.09 (C18)–5.27 (C1). There was a significant positive correlation between NFl and NFr on clusters during cultivation ($r = 0.939$, $P < 0.001$). Both NFl and NFr tended to decrease gradually during cultivation. C1 had the highest ratio of translation from flowers to fruits (89.4%). For C16, C17, and C18, these translations were the lowest (50–60%), and for the remaining, these ratios were less distinctly different among clusters (63%–81%). The wide variation in the standard deviation of the flowers and fruits quantities (e.g., C3, C8, C9, C12, and C16) indicated significant differences in NFl and NFr among the tomato clusters.

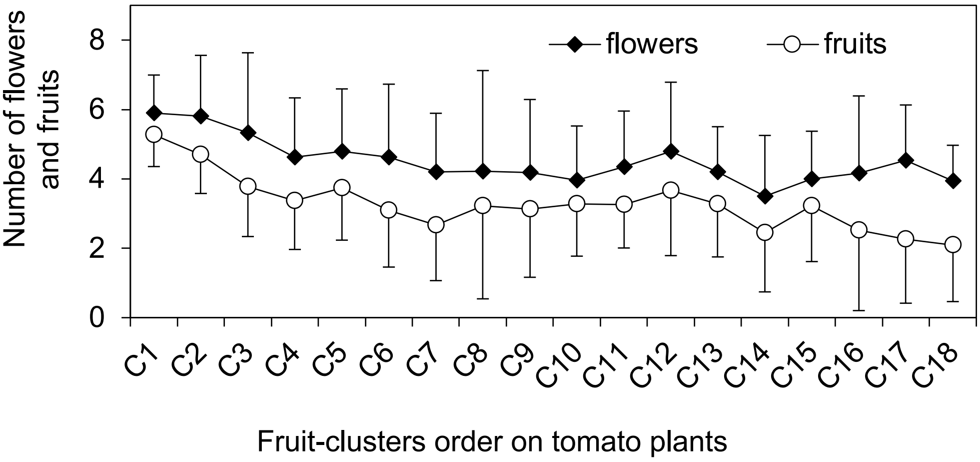

Fig. 4.3. The number of flowers translated into fruits on every tomato cluster of plants

NFr per cluster on tomato plants increased with increasing daily mean temperatures to an optimum level and then declined at a higher mean daily temperature, which was assumed because of impairing pollen and anther development and reduced pollen viability (Mary and Bartholemew, 1996; Sato et al., 2006; Uzun, 2007). These results agree with the fact that fruits number on C16, C17, and C18 apparently reduced when HU substantially increased later during cultivation (Fig. 4.2). Another reason why the proportion of flowers that became fruits significantly declined was because smaller VPD resulted from a higher relative humidity (RH) during pollination. More than 70% of RH during pollination would cause a poor or incomplete pollination of tomato flowers, and an RH greater than 90% (VPD less than 0.32 kPa) might increase pollen susceptibility to heat stress (Harel et al., 2014; Peet et al., 2003).

Fig. 4.4 shows the variation in the mean weight of fruit-clusters on tomato plants, whereby less than 500 g were C14 and C15, 600–800 g were C3, C4, C5, C6, and C13, and then greater than 800 g were C1, C2, C7, C8, C9, C10, C11, and C12. ANOVA indicated a significant difference in the weight of fruit-clusters on tomato plants ($n = 633$, $P < 0.001$). Tukey's HSD test ($\alpha = 0.05$) showed four weight groups; the first group included fruit-clusters C4, C14–15, the second C4, C6, C13, and C14, the third C2–13, and the fourth C1–2, C7–12.

The mean weight of fruit-clusters on tomato plants tended to decrease from C1 (1011.74 g)–C4 (696.78 g), then slightly fluctuated and increased to C11 (885.82 g), and finally reduced again from C12 (877.40 g)–C15 (473.50 g). The weight decline of the later fruit-clusters might result from the warmer air temperature during that period, which gradually rose and became higher (as presented in Figs. 4.1 and 4.2), consequently, buds opened faster (from approximately 30.65 to 24.69 days), fruits matured earlier (from approximately 66.96 to 43.21 days), the ripening time of fruits for harvest was sooner (from about 13.41 to 8.28 days), the perimeter of the fruits was smaller (from approximately 28.8 to 21.31 cm), and, its weight was lighter. This suggests a potential gap for cultivators to decide the desired size and weight of tomato fruits by controlling and maintaining appropriate temperatures.

There were similar fluctuations in CWt, NF1, and NFr. This was represented via the significant and positive correlations between CWt and NFI, CWt and NFr with the correlation coefficients were 0.801 and 0.809 ($P < 0.001$), respectively. Alternatively, the fluctuations in CWt were caused by the variation in fruit and flower numbers.

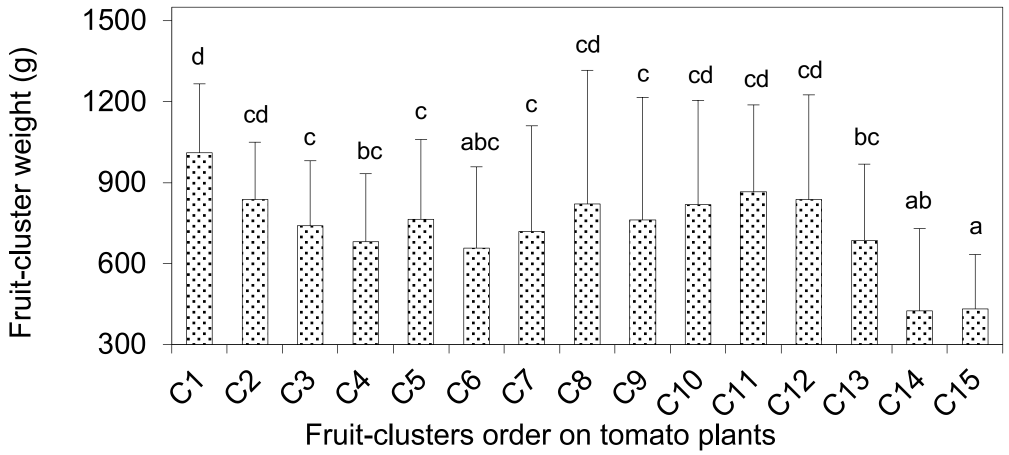

Fig. 4.4. The variation of fruit- cluster's weight on tomato plants (Notes: Tukey's HSD[a,b] analysis was employed, $\alpha = 0.05$. Groups sharing a common letter are not significantly different)

Fig. 4.5 presents the variation of fruit's perimeter on each tomato plants' fruit-cluster. It had an upward trend from C1 (25.49 cm) to C8 (28.80 cm), then decreased to C15 (21.31 cm). The wide variation of standard deviations (2.07–4.17 cm) indicated that the fruits' perimeter on a tomato-cluster were not homogeneous, C1 and C2 had the smallest differences in perimeter among fruits (approximately 2 cm) and increased in the later fruit-clusters (3.58–4.17 cm) during cultivation. Notably, there was a moderately significant and positive correlation between the PFr and CWt ($r = 0.643$, $P < 0.001$). However, there were high negative correlations between PFr and CHU ($r = -0.772$, $P < 0.001$), and moderate negative correlation with CSR ($r = -0.594$, $P < 0.001$). Thus, this implies that warmer temperatures and stronger SR would result in a smaller tomato fruit size.

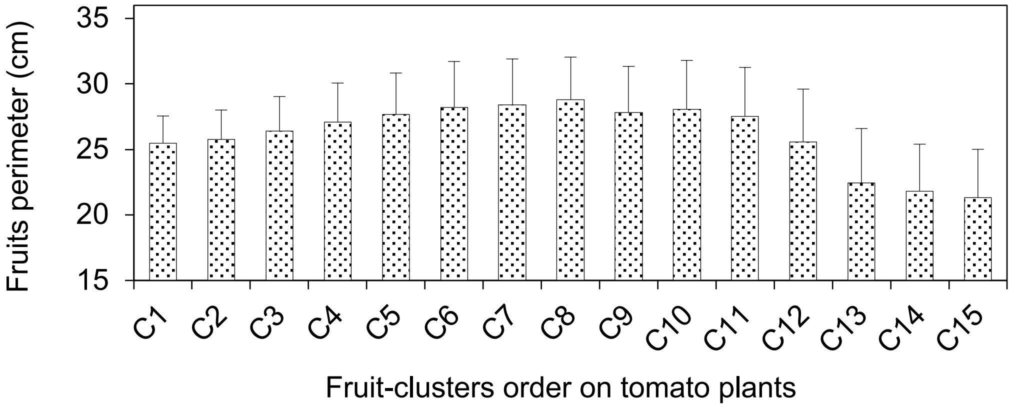

Fig. 4.5. The variation of fruit perimeter on each tomato plants fruit-cluster

Fig. 4.6 shows the mean fruit yield per tomato plant every two weeks during the harvest period from 24th January 2020 to the end of cultivation, 14th June 2020. The fruit yield fluctuated by 824.22–1203.63 g from the first harvest period (24th January–7th February) to the seventh harvest period (19th April–2nd May), suddenly increased to 1912.75 g in the eighth period (3rd–16th May), and then rapidly dropped to 434.06 g in the last period (31st May–14th June). The higher yield recorded in the eighth period (3rd–16th May) might have resulted when most of the fruits on tomato-clusters C10–12 were harvested during this period, also these clusters had a higher translation ratio from flowers to fruits (approximately 74–82%) and higher weight (approximately 819.58–865.22 g). The decline in yield per plant after 16th May might be due to the rapid decrease in PFr (approximately 21.31–25.59 cm), NFr (approximately 2.45–3.27), and CWt (approximately 426.13–685.54 g) of the later tomato plant fruit-clusters.

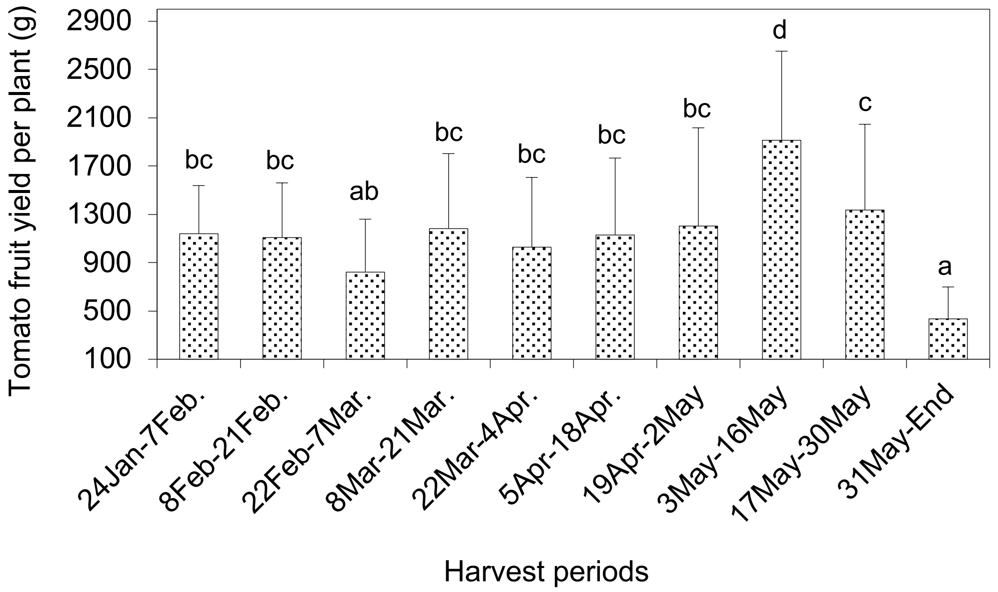

Fig. 4.6. Tomato fruit yield per plant in every two weeks (Notes: Tukey's HSD^{a,b} analysis was employed, α = 0.05. Groups sharing a common letter are not significantly different)

Besides, other studies revealed an increase in tomato fruit yield under a VPD of 0.8 kPa compared with plants grown with a VPD of 0.5 kPa, and there were higher yields under longer photoperiods and a lower VPD were maintained (Driss et al., 1995; Lu et al., 2015). However, a high VPD of 2.2 kPa could cause plant stress and reduce tomato fruit yield rapidly (Jiao et al., 2019; Leonardi et al., 2000). The fruit yield per plant in this study varied similar to these patterns, the higher yield in the latter days of April and in May 2020 followed the daily mean VPD of approximately 0.86–1.31 kPa. The photoperiods were longer in the summer (13.5–14.2 h.day^{-1}). After 30th May, when the VPD fluctuated between 2.9 and 3.2 kPa, the tomato fruit yield per plant substantially declined.

In practical cultivation, the temperature and RH often widely and sensitively fluctuated daily. As a result, the VPD is often unstable and difficult to control. Therefore, the effect of VPD on tomato fruit weight and yield is normally unapparent. This might explain why there was a moderate correlation between VPD and CWt ($r = -0.583$, $P < 0.001$) and weak correlation between VPD and yield ($r = -0.244$, $P < 0.001$).

4.3.3. CHU, CSR, VPD, and their mathematical models against the tomato cluster growth indices

Fig. 4.7 shows the duration of each development stage of the tomato clusters on plants. It took approximately 16.90–30.65 days for opening of buds (OB), 43.21–66.96 days for fruits maturation (FM), and 8.28–13.41 days for fruits ripening (FR). For OB, C5 to C10 took a longer time (approximately 27–30 days) than other clusters (approximately 16–25 days). For FM and FR, the duration tended to be longer in the initial fruit-clusters (approximately 60–67 days for FM and 9.0–13.5 days for FR), then gradually decreased in the later fruit-clusters.

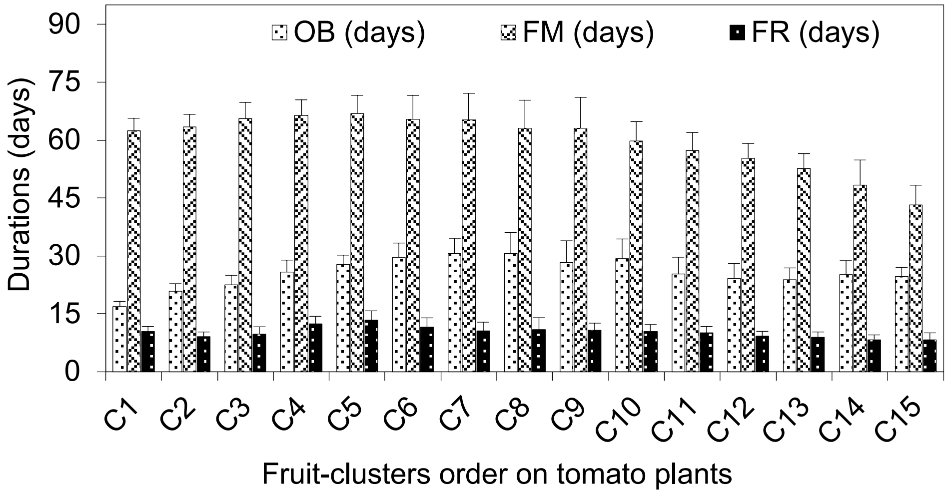

Fig. 4.7. The duration of tomato cluster's development stages (Notes: OB, FM, and FR are the duration of bud opening, fruit maturation, and fruit ripening)

Table 4.1 presents the correlation coefficients among tomato cluster growth indices and environmental factors throughout tomato growth in a glass greenhouse. There was a very high positive correlation between NFl and NFr (r = 0.939); and high and moderate positive correlations between CWt and NFl (r = 0.801), NFr (r = 0.809), and PFr (r = 0.643). Meanwhile, there were negative correlations between CHU, CSR, and growth indices with correlation coefficients of –0.526 to –0.916 for CHU, and –0.594 to –0.802 for CSR. In terms of correlations between VPD and growth indices, except for the positive correlations with NFl (r = 0.645) and NFr (r = 0.801), all other correlations were negative with correlation coefficients between –0.557 and – 0.957. Lastly, there were high positive correlations between mean VPD and CHU (r = 0.807), and CSR (r = 0.852), between CHU and CSR (r = 0.924).

Table 4.1. Correlation coefficients (r) among growing and environmental indices

	OB (days)	FM (days)	FR (days)	NFl	NFr	PFr (cm)	CWt (g)	CHU (unit.day^{-1})	CSR (MJ.m^{-2}.day^{-1})	VPD (kPa)
OB (days)	1	0.198	0.419	– 0.673	– 0.765	0.517	– 0.253	– 0.916	– 0.765	– 0.848
FM (days)		1	0.784	0.684	0.503	0.851	0.717	– 0.859	– 0.802	– 0.821
FR (days)			1	0.327	0.219	0.743	0.426	– 0.876	– 0.771	– 0.593
Number of flowers (NFl)				1	0.939	0.365	0.801	– 0.699	– 0.840	0.645
Number of fruits (NFr)					1	0.213	0.809	– 0.526	– 0.745	0.801
Fruits perimeter (PFr, cm)						1	0.643	– 0.772	– 0.594	– 0.818
Clusters weight (CWt, g)							1	– 0.725	– 0.666	– 0.583
CHU (unit.day^{-1})								1	0.924	0.807
CSR (MJ.m^{-2}.day^{-1})									1	0.852

Notes: OB, FM, and FR are the duration of bud opening, fruit maturation, and fruit ripening, CHU is cumulative heat unit, CSR is cumulative solar radiation, VPD is the vapor pressure deficit, NFl is the number of flowers, NFr is the number of fruits, PFr is the perimeter of fruits, and CWt is the fruit-cluster's weight.

These results imply that CSR had a stronger effect on NFl rather than CHU and VPD, meanwhile, NFr much relied on VPD than CHU and CSR. Thus, suggesting that pollination condition would be sensitive to VPD. Fruits number and enlargement of fruit cells during maturation might be important factors for CWt and plant yields. Such findings were revealed through the correlations between plant yields and NFl (r = 0.835), NFr (r = 0.872), PFr (r = 0.575), and CWt (r = 0.727). Besides, results revealed that when FM's duration was longer, the growth indices also became bigger, then finally resulting in increased plant yield. Therefore, the estimation of FM duration can strongly predict the yield, and FR estimation can be applied for harvest time determination.

Ideally, PFr will have a strong positive correlation with CWt; however, here, the correlation was moderate (r = 0.643). This implies that fruit size is the main factor affecting fruit weight and plant yield, but the fruit structure and the number of fruit cells might be another significant factor.

Table 4.2. Variables data used for mathematical models by multiple linear regression.

Variables		Min.	Max.	Avg.	SD.
OB (n = 336)	Duration (days)	14	39	25.51	5.95
	HU (units.day^{-1})	417.66	1694.95	1009.80	333.95
	SR (MJ.m^{-2}.day^{-1})	5.15	20.07	11.21	2.49
	VPD (kPa)	0.67	2.07	1.11	0.40
FM (n = 435)	Duration (days)	37	76	60.53	8.27
	HU (units.day^{-1})	551.98	1952.21	843.25	335.66
	SR (MJ.m^{-2}.day^{-1})	7.44	20.38	11.39	3.93
	VPD (kPa)	0.69	1.77	0.92	0.25
FR (n = 217)	Duration (days)	6	18	11.06	2.93
	HU (units.day^{-1})	638.46	2494.65	1517.89	474.51
	SR (MJ.m^{-2}.day^{-1})	8.62	26.85	16.67	4.17
	VPD (kPa)	0.71	3.23	1.27	0.33

Notes: n: number of samples; Avg.: average; SD.: standard deviation

Table 4.2 presents the basic information on the descriptive statistical analysis of variables applied for mathematical models by multiple linear regression. The number of OB, FM, and FR observations was 336, 435, and 217; these ranges were from 14–39, 37–76, and 6–18 days, respectively. The daily HU for OB, FM, and FR ranged from 417.66–1694.95, 551.98–1952.21, and 638.46–2494.65 units.day^{-1}; the daily SR for OB, FM, and FR fluctuated from 5.15–20.07, 7.44–20.38, and 8.62–26.85 MJ.m^{-2}.day^{-1}, respectively; and the daily VPD for OB, FM, and FR varied from 0.67–2.07, 0.69–1.77, and 0.71–3.23 kPa, respectively. In the later periods of cultivation, the daily HU of FR was higher than that of OB and FM. This was because the daily temperature was warmer after February 2020 (as shown in Fig. 4.1).

Table 4.3. Results of multiple linear regression (MLR) for growth indices against CHU, CSR, and VPD.

Models	Equations	Relative importance metrics (RIM) of predictor variables in MLR(%)			R^2	RMSE	PER (%)
		[CHU]	[CSR]	[VPD]			
1	OB = 45.5278‘***’ – 0.0163[CHU]‘***’ – 0.5671[CSR]‘***’ + 2.5504[VPD]‘**’	37.44	22.46	27.91	0.878***	2.079	8.15
2	FM = 80.2388‘***’ – 0.0184[CHU]‘***’ + 0.2012[CSR]‘ ’ – 7.0363[VPD]*	29.47	21.55	23.18	0.742***	4.194	6.93
3	FR = 21.4656‘***’ – 0.004[CHU]‘***’ – 0.2627[CSR]‘***’ + 0.0303[VPD]‘ ’	43.66	28.96	12.68	0.853***	1.126	10.18
4	NFl = 228.9488‘***’ – 0.0704[CHU]‘*’ + 0.0596[CSR]‘ ’ + 122.7154[VPD]‘**’	28.77	36.83	20.12	0.857***	26.844	13.12
5	NFr = 134.3466‘***’ – 0.0692[CHU]‘*’ + 0.0723[CSR]‘.’ + 147.8566[VPD]‘***’	20.08	31.46	37.37	0.889***	17.565	11.27
6	PFr = 23.9872‘***’ – 0.0274[CHU]‘***’ + 1.0288[CSR]‘***’ + 15.3765[VPD]‘ ’	39.46	25.72	30.16	0.953***	0.774	2.96
7	CWt = 7068.051‘***’ + 6.227[CHU]‘*’ + 353.665[CSR]‘*’ – 15277.07[VPD]‘**’	23.32	23.15	29.37	0.758***	326.957	14.83

Notes: OB, FM, and FR are the duration of bud opening, fruit maturation, and fruit ripening. NFl is the number of flowers, NFr is the number of fruits, PFr is the fruit perimeter, and CWt is the fruit-cluster’s weight. RMSE is the root mean square error; it was calculated from 10-fold cross-validation with three-time repetition using the caret-package. PER is the prediction's error rate, which was calculated by dividing RMSE from the mean of observed data. Significant codes: ‘***,’ ‘**,’ ‘*,’ ‘.’, and ‘ ’ indicate significant levels at $P < 0.001$, 0.01, 0.05, 0.1, and 1, respectively.

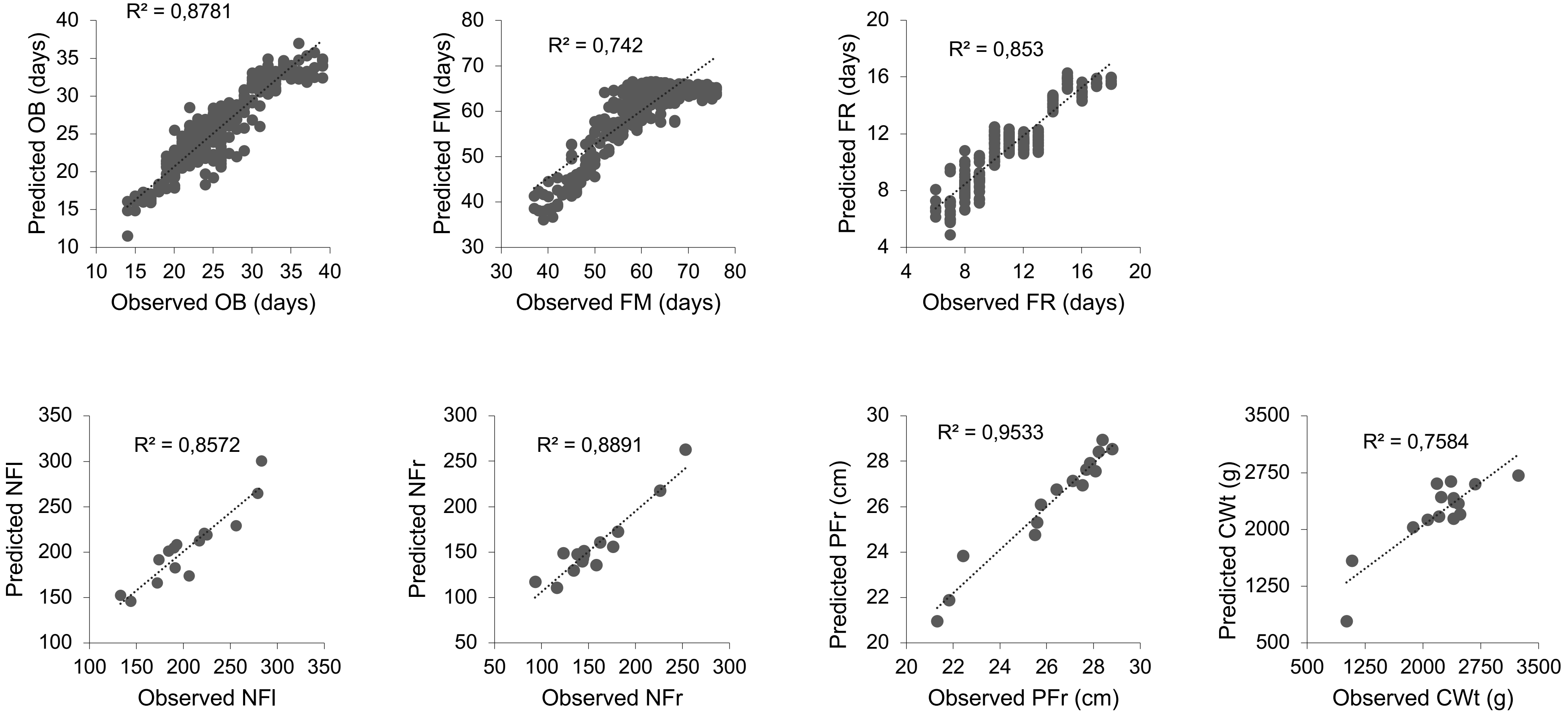

Fig. 4.8. Prediction of tomato cluster growth indices between observed and predicted data by scatter plots

Table 4.3 shows the mathematical models established by MLR in the duration of OB, FM, and FR, NFl, NFr, PFr, and CWt as response variables against corresponding CHU, CSR, and VPD as predictor variables. There were respectively 87.8%, 74.2%, and 85.3% variations in durations of OB, FM, and FR explained by CHU, CSR, and VPD in MLR. Simultaneously, for NFl, NFr, PFr, and CWt were 85.7%, 88.9%, 95.3%, and 75.8%, respectively. The prediction error rate (PER) of models was between 2.96% and 14.83%, the least was at model six of PFr and higher at model seven of CWt. Throughout the models, CHU's RIM dependently accounted for 20.08–43.66%, CSR for 21.55–36.83%, and VPD for 12.68–37.37%. These coefficients of determination (R^2) and the prediction (PER) error rate indicate that CHU, CSR, and VPD have high potentials for the prediction and estimation of these tomato cluster growth indices.

In these seven models, models one, two, three, and six indicated that CHU was the most important factor, which affected tomato cluster's duration (OB, FM, and FR) and PFr. The regression coefficients of CHU in those MLR models represented negative effects on those corresponding response variables. This implies that the greater the CHU the shorter the OB, FM, and FR duration, and the smaller the PFr. These were in agreement with the findings by Adams, who reported that the duration for maturation and ripening of fruits were longer when plants were grown under lower temperatures (Adams et al., 2001). Similarly, CSR had a negative relationship with OB, FM, and FR duration.

Meanwhile, the fourth model for NFI indicated that CSR was the most significant factor (accounting for 36.83%). Its regression coefficient in the MLR model showed a positive value, which indicated that NFI would increase with increasing CSR. Similar tendencies were confirmed in models five, six, and seven. Lastly, the fifth and seventh models for NFr on each cluster and CWt revealed that VPD was the most crucial factor. This might because of the important roles VPD perform in controlling plants' water uptake, which affects transpiration, pollination, growth, quality, and yield of tomato fruits (Shamshiri et al., 2018), and directly effects the radiation use efficiency of tomato plants (Stockle and Kiniry, 1990). This was also revealed through the significant positive relationship between NFr and VPD (r = 0.801) and CWt (r = 0.809). The fifth model suggests that VPD was an important index during pollination, which accounted for 37.37% compared with 20.08% in CHU and 31.46% in CSR.

Further, as shown in Table 4.1, there were negative correlations between OB, FR, PFr, and VPD; between FM, NFI, NFr, PFr, CWt, and CSR; and between CWt and CHU. However, in corresponding MLR models, which have three predictor variables, those effects were expressed in the opposite trend. These findings imply that the interaction and combination impact of environmental factors on tomato growth indices are complex, applying separately a mono factor to describe plant growth conditions is insufficient and may result in bias explanation and estimation, also considering sufficient micro-environmental indices during tomato cultivation is useful and necessary for gaining higher fruit yield.

Cross-validation analysis of MLR models revealed that there were no large discrepancies between the predicted-R^2 and R^2 values (a predicted-R^2 that is distinctly smaller than R^2 is a warning sign of overfitting the model. In this study, this discrepencies were between 0.35% and 17.76% among 7 mathematical models for growing indices). This means that those models have the potential for predicting new observations, also they fitted well in the original observational data. Alternatively, these models were generalizable and showed less signs of overfitting. Also, for prediction and estimation using MLR models, collinearity is a common issue when there are high correlations among predictor variables, leading to unreliable and unstable estimates of regression coefficients. Especially during practical greenhouse cultivation, correlations between environmental factors, such as temperature, solar radiation, and humidity are unavoidable. These were indicated through correlations among CHU, CSR, and VPD in this study, where correlation coefficients were between 0.807 and 0.924. However, these relationships were incompletely perfect ($r = 1$) among the predictor variables, which means that there are still gaps in the mathematical model improvement through MLR.

Temperature, humidity, and solar radiation are environmental indices, which are easy to record and monitor. However, they vary and fluctuate substantially with time under the undeniable impacts of climate change.

Accordingly, simply and directly applying these indices for evaluating, describing, and predicting the plants' physiological reaction is unreliable and inaccurate. This study proves that CHU, CSR, and VPD are potential indices to describe and predict the growth indices of tomato clusters through mathematical models. These models can be applied to well-controlled environmental conditions during greenhouse cultivation to attain the desired fruit yield at a specific time and fulfill market demand.

4.4. Conclusions

The study presented the effects of environmental factors (CHU, CSR, and VDP) on the growth and development of tomato clusters (Momotaro Haruka variety) during greenhouse cultivation and the ability to build mathematical models from those factors for describing the growth and development of a tomato cluster (NFl, NFr, PFr, CWt, and duration of OB, FM, and FR). The significant correlations between these environmental factors and tomato cluster growth indices indicated a potential capacity to apply mathematical models for predicting the duration of cluster development; estimating the number of fruits on a tomato cluster, fruit size, weight and harvest time of fruit-clusters; and prolonging the desired harvest yield of tomato plants by maintaining ideal cultivation conditions. Mathematical models via MLR analysis indicated that CHU was the most important factor in the duration of a tomato cluster development and fruit perimeter; CSR was the significant variable for the number of flowers in each cluster; and VPD was the crucial factor for fruit number on each cluster and the fruit-cluster's weight. Further experiments should be conducted to determine the controlled-daily mean temperature, -light intensity, and -humidity, and delve into the co-effects of CHU, CSR, and VPD on the duration of tomato cluster development, division, and enlargement of fruit cells to clarify the relationships between those indices and tomato fruit yield per cluster as well as the whole plant during cultivation.

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CHAPTER 5

CONCLUSION

This study investigated the effects of environmental factors such as temperature, solar radiation, humidity, and their cumulative indices as the cumulative heat unit (CHU), the cumulative solar radiation (CSR) and vapor pressure deficit (VPD) related to duration of flower-clusters occurrence (DFO), the opening of flower-buds (OB), the maturation (FM), and the ripening of fruits (FR), the number of flowers (NFl), number of fruits (NFr), fruit perimeter (PFr), and the fruit-cluster weight (CWt) by mathematical models using multiple linear regression (MLR).

The findings proved that CHU, CSR, and VPD were potential indices to describe and predict the growth characteristics of tomato clusters through mathematical models. CHU and CSR had a significant impact on the occurrence of flower-clusters (r^2 = 0.94, RMSE = 0.71), especially CSR indicated stronger effect on NFl rather than CHU and VPD. There was a strong significant relationship between CHU and DFO (r^2 = 0.93, RMSE = 0.73). Meanwhile, NFr relied much on VPD than CHU and CSR. Also, pollination condition was sensitive to VPD, NFr and FR were important factors in fruit-cluster weight (CWt). MLR models could explain growth indices of tomato cluster with the coefficient of determination (R^2) from 0.742 to 0.953. These mathematical models via MLR indicated that CHU was the most important factor in DFO and PFr, CSR was the significant variable for NFr in each cluster, and VPD was the crucial factor for NFr on each cluster and CWt.

By using those models, DFO will be concreated as the base date of the plant growth phase and will contribute to clarify in-detailed plant growth phases. These models can be applied to well-controlled environmental conditions during greenhouse cultivation to attain the desired fruit yield at a specific time or maintain a stable yield throughout the year.

Further research could focus on the impact of temperature and solar radiation on the stem elongation capacity of tomato plants to clarify the relationships between those environmental factors, growth rate, and the occurrence of flower-clusters. In addition, other experiments can be conducted to determine the controlled-daily mean temperature, -light intensity, and -humidity, and delve into the co-effects of CHU, CSR, and VPD on the duration of tomato cluster development, division, and enlargement of fruit cells to clarify the relationships between those indices and tomato fruit yield per cluster as well as the whole plant during cultivation.