Article

Application of the Climograph for the Greenhouse Plan of Subtropical and Tropical Regions

Chiachung Chen

Department of Bio-Industrial Mechatronics Engineering, National Chung Hsing University, 250 Kuokuang Road, Taichung 40227, Taiwan; ccchen@dragon.nchu.edu.tw; Tel.: +886-4-22857562; Fax: +886-4-22857135

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Abstract: The technological levels of greenhouse influence significantly the yields of the crop production and increase the investment cost. The balance between the development of the technological level and the achieving of the increased crop production in the controlled environment is always the primary concern. In this study, the climograph was obtained by plotting the mean minimum monthly temperature versus mean maximum monthly temperature. This climagraph was combined at the optimum temperature ranges of three fruit vegetables and a simple microclimate model was introduced to evaluate the controlling performance of internal air temperature in greenhouses. In subtropical areas, seven locations were selected in order to demonstrate the application of the climograph for the cultivation of species. The rotation of temperate and thermophile plant in Yulin, Taiwan was proposed. Melon, as the thermophile crop, was the only crop that could be cultivated in greenhouses in the two locations of low land areas. The results in three locations of high land areas indicated that all temperate vegetables were suited well to be cultivated in these areas. Thus, the significant highlight of this method was that it could also be successfully used for other species at different locations for the greenhouse production to reduce the energy consumption.

Keywords: climograph; greenhouse plan; subtropical; tropical; fruit vegetables; energy consumption

1. Introduction

Greenhouses are widely spread around the world. The purpose of a greenhouse is to maintain an optimum environment for plant production. The microclimate in the greenhouse is mainly influenced by the local weather, structure and covering materials of greenhouses, and controlling equipment [1].

Despite greenhouse shelters, crops from peripheral bad weather, high temperature and humidity, during hot days could cause adverse effects on crop production in tropical regions [2]. Hence, in such regions, controlling or regulation of air temperature inside the greenhouse closer to the ambient temperature is essential for effective crop production. So, in order to overcome the glitches due to high temperature, cooling is considered as the basic requisite for greenhouse crop production in tropical and subtropical regions [3–6]. Development of a potential cooling system that affords an amiable microclimate for crop growth remains a difficult task, as the design is closely related to the local environmental conditions [7]. Moreover, selection of appropriate technology for cooling mainly depends on the choice of the crops to be cultivated, maintenance, ease of operation, and economic viability. Hence, better understanding of the physical processes of the greenhouse could help in the development of suitable cooling system [8].

Two technical levels of greenhouses, such as low-tech and high-tech, were proposed by Stanghellini et al. [2]. The low-tech greenhouse only causes a limited control ability of temperature by opening the top or side vent and shading nets. The high-tech greenhouse can potentially control the temperature through ventilation and heating, and regulate the humidity through ventilation and
fogging. In the low-teach greenhouse, microclimate is controlled manually, and in the high-tech greenhouse, the microclimate is controlled by computers [2,9].

Three technical levels of greenhouses, such as low-tech, medium-tech, and high-tech, were stated by Nursery and Garden Industry, Australia [9]. The low-tech greenhouses are of relatively simple structure, cheap, and easy to build. They cause only minimal control ability by natural ventilation for the growing environment. Medium-tech greenhouses are usually set with the higher vertical walls and roof, and side wall ventilation system and basic level of automatic control, with or without heating. High-tech greenhouses have all kinds of environment control equipment and a computer-driven control system. The insect screen, thermal screen, and specialized coverings are typical utilization materials and the control system is completely computerized. This greenhouse is suited well to a significant impressive range of crops and full automated environmental control performance. Therefore, it is considered to provide the potentiality for maximal productivity of crops [2,10].

In the subtropical and tropical regions, rain shelters are used to keep the crops out of heavy rain. However, the air temperature and humidity in the shelter are usually comparatively higher than that of the ambient air. The high temperature in spring and summer, and marginal light and low temperature in winter, are considered as the weather characteristics for subtropical regions. For tropical regions, high temperature and radiation are the major factors significantly affecting the vegetable growth [3,4,7].

The level of technology applied in the greenhouse is mainly related to the investment. With the higher level of the applied technology, there is the greater potential for achieving the controlled microclimate in the greenhouse [3,9,10].

The basic concern for greenhouse production always remains among three levels, in which greenhouses can offer the best balance between cost and the yield and quality of production. The important aspects of local weather and the optimum culture environment of crops are considered as major controlling factors [2,9–11].

A climograph was used to express the important weather information on the same graph. Nisen et al. [11] first introduced the application of the climograph for the assessment of the environmental control requirement for the climate suitability in Almeria, Spain. The mean solar radiation was plotted in the Y-axis and mean monthly air temperature was plotted in the X-axis. Analysis of this study indicates that the environmental control strategies for the thermophilic vegetable species included heating, passive natural ventilation, and cooling.

Kittas [12] introduced climographs for four different regions of Greece in order to evaluate the suitability of the crops under greenhouses covered with plastic film. In these climographs, the average monthly minimum and maximum air temperature (X-axis) versus the global irradiance (Y-axis) was plotted. Fitz-Rodriguez et al. [13] used a climograph that plotted the average photosynthetic photon flux versus average daily air temperature for every month of four locations to demonstrate the dynamic models of greenhouse environments. De Pascale and Stanghellini [14] described a climograph by plotting the mean temperature in the X-axis and mean solar radiation in the Y-axis for the Netherlands and South Italy. They discussed the requirement of climatic controls for greenhouse vegetable crop cultivation based on different controlling techniques such as closed and continuously ventilated, heating at night/day, heating night, and no heating.

Zabeltitz [10] introduced two types of climographs to discuss the main climate requirements of crop cultivation and the operation of the equipment in greenhouses. The first climograph was obtained by plotting the mean solar radiation (Y-axis) versus mean daily temperature (X-axis), and the other was obtained by plotting the mean minimum temperature versus mean maximum temperature. Kittas et al. [15] used a climograph of two regions in the Mediterranean by plotting the mean solar ration (Y-axis) and the mean air temperature (X-axis) to show the required periods of ventilation and heating of greenhouses, and found that the day temperature of Almeria, Spain and Volos, Greece were too high to use the ventilation in summer.

Tuzel and Oztekin [16] compared the temperature conditions between Almeria, Spain and Antalya, Turkey with the climograph obtained by plotting the mean minimum temperature (Y-axis)
versus mean maximum temperature (X-axis). Three control operations such as heating, ventilation, and cooling were proposed in different months. George et al. [17] selected climographs of four regions of Greece to build a culture plan of four kinds of vegetable species: Cucumber, tomato, lettuce, and pepper.

In tropical and subtropical weather (except some regions in winter), as the solar radiation is so high, the shade nets are used to avoid leaf burn and heat stress. It is also stated that solar radiation is not the factor for growth of vegetable in these regions. However, temperature is the key factor to be considered for the culture plan [2,8,10]. The scientific question is how to assess the greenhouse production plan in tropical and subtropical climates by adequate climographs. The scientific hypothesis is what an adequate climograph for tropical and subtropical weather is. In the novelty technology of this study, the climograph is defined as the mean minimum monthly temperature versus mean maximum monthly temperature, and these climographs are combined at the optimum temperature ranges of fruit vegetables. Based on this, a culture plan is proposed for several regions in tropical and subtropical weather.

2. Materials and Methods

2.1. The Greenhouse Microclimate Model and Internal Air Temperature

The following four categories were the main influencing factors on the greenhouse microclimate:
1. Atmosphere conditions: Air temperature, humidity, solar radiation, wind speed, and direction, etc.
2. The structure and covering materials of the greenhouse.
3. Equipment and its capacity: Shading nets, fans, pad/misting, heater, conditioners, etc.
4. Crop: Varieties, culture stage, growing area, etc.

The development of a simple greenhouse microclimate model to express the factors affecting the internal temperature and controlled ability of equipment is very useful. The schematic representation of a typical greenhouse is presented in Figure 1.

![Figure 1. Schematic diagram of the thermal transfer model for a greenhouse.](image)

The assumptions of this model are as follows:
1. No existence of temperature gradient in each layer.
2. Constant heat transfer coefficients of covering materials.
3. The steady state of temperatures of the internal air, crops, and covering materials.
4. Crops were planted in soil. The ground was covered with weed-inhibiting nets. The thermal energy of soil was not considered since the crops covered most of the ground.

More complicated models were extended and validated from this simple model. They included the gradient temperature and humidity in a pads/fans greenhouse [18], the temperature distribution within two layers of shading nets [19], and the misting cooling in an Oncidium greenhouse [20].

2.1.1. The Input Energy

\[ Q_{in} = \tau \times I_s \]  

where \( Q_{in} \) is the solar energy in the greenhouse in Wm\(^{-2}\); \( \tau \) is the transmittance of shading nets; and \( I_s \) is the entrance energy of shortwave radiation from the sun in Wm\(^{-2}\).

2.1.2. The Output Energy

1. \( Q_c \): Energy exchange by heat transfer

\[ Q_c = K \times A_w \times (T_i - T_a) \]  

where \( A_w \) is the surface area of the greenhouse, including the roof and wall in m\(^2\); \( K \) is the heat transfer coefficient of the greenhouse covering materials in Wm\(^{-2}\) K\(^{-1}\); \( T_i \) is the air temperature in greenhouse in °C; and \( T_a \) is the ambient temperature in °C.

2. \( Q_v \): Energy exchange by ventilation

\[ Q_v = N \times \rho \times C_p \times (T_e - T_a) \]  

where \( N \) is ventilation rate in m\(^3\) s\(^{-1}\); \( \rho \) is the air density in kg m\(^{-3}\); \( C_p \) is the air specific heat in J kg\(^{-1}\) °C\(^{-1}\); and \( T_e \) is the temperature of entering air.

3. \( Q_p \): Transpiration energy by crops

\[ Q_p = \lambda \times T_r \times F \times A_f \]  

where \( \lambda \) is latent heat of vaporization in kJ kg\(^{-1}\); \( T_r \) is transpiration rate of crops in kg m\(^{-2}\); \( A_f \) is the floor area of greenhouse; and \( F \) is the canopy area index.

4. \( Q_m \): Energy exchange by equipment

The \( Q_m \) is determined by the capacity of equipment.

The energy balance equation is:

\[ Q_{in} = Q_c + Q_v + Q_p + Q_m \]  

Substituting all items into Equation (5), the internal air temperature can be expressed as follows:

a. 

\[ T_i = \frac{\tau \times I_s \times A_f + K \times A_w \times T_a + C \times N \times T_e - \lambda \times F \times T_r \times A_f + \frac{Q_m}{K \times A_w + C \times N}}{(K \times A_w + C \times N)} \]  

b. If no cooling device (pads/misting) or equipment are used, \( T_e = T_a \) so the \( T_i \) is:

\[ T_i = T_a + \frac{\tau \times I_s \times A_f - \lambda \times F \times T_r \times A_f}{K \times A_w + C \times N} \]  

2.1.3. The Effect of Ventilation Rate
The ventilation rate is \( N \), and other factors are integrated as constant. Equations (6) and (7) can be modified as follows:

\[
T_i = T_a + \frac{K_1}{K \times A_w + C \times N} \tag{7}
\]

\[
T_i = \frac{C \times N \times T_a - K_2}{K \times A_w + C \times N} = \frac{T_a - K_2}{C \times N} \times \frac{1}{K \times A_w + C \times N + 1} \tag{8}
\]

In a natural ventilation condition, the ventilation rate is limited. The internal air temperature is higher than ambient air temperature, \( T_i > T_a \).

If the ventilation rate of mechanical fans is very high, the \( N \) value in Equations (8) and (9) is assumed to be infinite. So \( K_2/(C \times N) \) can be assumed to equal to zero. The internal air temperature is the same as ambient air temperature. \( T_i = T_a \).

If the cooling equipment is used and the ventilation rate of mechanical fans is very high, \( K_2/(C \times N) \) and \( K \times A_w/(C \times N) \) can be assumed to equal to zero. The internal air temperature is the same as entering air temperature. \( T_i = T_e \). The \( T_e \) is determined by the ambient air wet-bulb temperature and the cooling efficiency of cooling equipment.

2.1.4. Effect of Crops

The other factors are integrated as constant \( K_3 \), Equation (6) is rearranged as:

\[
T_i = T_a + \frac{K_1 - \lambda \times F \times Tr}{K_4} \tag{9}
\]

As the increase of planting ratio \( F \), the decrease of the internal air temperature.

The larger the \( Tr \) value is, the better the cooling ability of the crops is. Fruit vegetables possessed larger \( Tr \) values than other vegetables.

2.2. Modifying Internal Air Temperature of Greenhouse

On a sunny day, the greenhouse air could be heated due to the greenhouse effect. The cooling methods for reducing air temperature include natural ventilation, mechanical ventilation, evaporative cooling, and air conditioner.

In the case of ample ventilation, the internal air temperature could be closed to the ambient temperature. Because of the high humidity in subtropical and tropical regions, the cooling ability of evaporative cooling is limited. The internal air temperature could be 5–7 °C lower than that of the outside air temperature [5,18]. The pads/fans system has higher evaporative efficiency than that of misting or fogging, and it is easy to control the water consumption [5]. However, the structure of greenhouse installed pads and fans must be stronger than that of using misting or fogging [18]. The utilization of conditioners is too expensive to apply, except for some very high economical crops, such as the spiking and flowering of Phalaenopsis.

At nighttime, hot air or water heaters are common techniques. It is stated that evaporative cooling does not help due to the saturation of the moisture of the air. The only way to cool down the air temperature at night in a greenhouse is to use conditioners, but the cost is very high [3–5,7].

2.3. Microclimate Requirements of Crops

Three species—tomato, cucumber, and melon—grown in greenhouses show the range of general temperature requirements as listed in Table 1.
Table 1. The temperature requirement of three fruit vegetables.

<table>
<thead>
<tr>
<th>Species</th>
<th>Optimum day temperature</th>
<th>Optimum night temperature</th>
<th>Limited temperature of growing</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gruda et al. [24] Baudoin et al. [25]</td>
</tr>
<tr>
<td>Cucumber</td>
<td>20–30 °C</td>
<td>17–22 °C</td>
<td>13 °C</td>
<td>Bonzo [26]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Balliu and Sallaku [27]</td>
</tr>
<tr>
<td>Melon</td>
<td>25–33 °C</td>
<td>18–24 °C</td>
<td>15 °C</td>
<td></td>
</tr>
</tbody>
</table>

Note: Solar radiation in subtropical and tropical regions is pretty high, except in some subtropical regions in the winter time. Light intensity is not a limit factor. External and internal shading nets are usually used to reduce the entering radiation in the greenhouse. So the light requirement is not discussed in this study.

3. Results

3.1. The Requirement of Environmental Control

The range of the optimum day and night temperature for special species was combined in the climograph, defined as the mean night (minimum) temperature on the Y-axis and the mean day (maximum) temperature on the X-axis, as shown in Figure 2. In Figure 2, it is observed that nine zones were divided based on the requirement operations in each zone. For Zone I, cooling was required both in the day and at nighttime. Cooling was required in the day and at night, and temperature was optimum in Zone II. Day temperature was optimum, however, cooling was required at night in Zone III. Day and night temperatures were optimum in Zone IV. For Zone V, day temperature was optimum and heating was required at night only. Heating was required in the day and at night for Zone VI.
Figure 2. The combination between the climograph and the optimum temperature ranges of crops in the greenhouse. $T_{DL}$, optimum day low temperature; $T_{DH}$, optimum day high temperature; $T_{NL}$, optimum night low temperature; $T_{NH}$, optimum night high temperature. All temperatures mentioned above are the outside temperatures.

Three zones seldom exist, as discussed as follows: They were Zone X1, where heating was required in the day and cooling was required at night; Zone X2, where night temperature was optimum and heating was required in the day; and Zone X3, where cooling was required in the day and heating was required at night. Such three zones were not be considered in this study.

3.2. Subtropical Region

3.2.1. Yulin, Taiwan

The climographs of Yulin, Taiwan and the range of optimum temperature for three fruit vegetables—tomato, cucumber, and melon—are shown in Figure 3.

![Climographs of Yulin, Taiwan and the range of optimum temperature for three fruit vegetables.](image-url)
Figure 3. The combination of climographs of Yulin, Taiwan and the range of optimum temperature for three fruit vegetables: (a) Tomato; (b) cucumber; (c) melon.

In Figure 3a, the local mean day and night temperature of each month are presented as the coordinate points. Three zones were represented for the tomato production. At Zone I, from May to October, the day and night temperatures were too high to cultivate the tomatoes, and the only method...
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to reduce the night temperature was to use conditioners, which was considered cost-wise as an uneconomical way. Zone II included March, April, and November months, when the day temperature was higher than optimum temperature but lower than survival temperature. Zone V, from December to February of the next year, heating was required in night. However, the minimum temperature was higher than the low temperature limit.

The production plan of tomato in Yulin region was proposed as follows:

a. All year round cultivation

The greenhouse needed to keep air-tight and install complex equipment, especially heaters and air conditioners. The energy consumption for operating air conditioners to reduce the day temperature in summer is very high.

b. Half-year cultivation

Tomatoes were planted from November to the March of the next year. In December, January, and February, the day temperature was higher and night temperature was lower than the optimum temperature. However, it still stayed in the growing environment. In this case, the highest yield and best quality were not observed in half-year culture, but this was considered as economically the cost effective method.

Figure 3b shows the coordinate points of each month for cucumber. It was observed that results were quite similar to the case of tomato. Zone I indicates the periods during which cucumber was not easy to grow without using air conditioners. For Zone V, heating was required at night in these three months in order to obtain better yields and good quality. Similar to the required conditions of tomato, the night temperature in the greenhouse was not at optimum condition. Six-month culture periods (from November to May of the next year) were reasonable.

The optimum temperature for melon combined in the climograph of Yulin, Taiwan is shown in Figure 3c. Four zones were involved in this case. In Zone II, cooling was required in the day during June and July. It was stated that misting was a practical method to reduce the day temperature. Zone IV existed in this period, and represented the optimum conditions of cultivation of melon during six months. In the other four months, December, January, February, and March, heating was required at night.

If melon was cultivated all year round, misting in summer and heating in winter were suggested as the essential techniques. However, it was very difficult to control humidity in the greenhouse using misting or fogging techniques for the high humidity in subtropical regions. However, only half-year periods were suitable for this species.

Based on the above discussion, the rotation of crop species was stated as the reasonable way for fruit vegetables in Yulin, Taiwan. Tomato or cucumber was cultivated from November to April of the next year and the melon was cultivated in summer from June to September. This crop rotation scheme was suggested as the best combination considering the crop microclimate requirement and the cost of environment control.

It could be mentioned that if the tomato or cucumber was planted all year round, the cost of cooling in summer would be highly expensive and if the melon was cultivated all year round, the cost of heating in winter would be uneconomical. The cultivation of two species at the different periods in the same greenhouse was suggested as the best way.

3.2.2. Tainan, Taiwan

The climograph of Tainan, Taiwan and optimum temperature of three species are shown in Figure 4.
(a) Tomato

I. Cooling in the day and at night
Ⅰ. Cooling in the day
Ⅴ. Heating at night

(b) Cucumber

IV. Optimum
Ⅳ. Optimum
Ⅴ. Heating at night
Figure 4. The combination of climographs of Tainan, Taiwan and the range of optimum temperatures for three fruit vegetables: (a) Tomato; (b) cucumber; (c) melon.

From Figure 4a, it is observed that most of the months were located in Zone I, where cooling in the day and at night is required from April to November. It was considered as an uneconomic for cooling control in the day and at night for a long time. The other months, May as located in Zone II, cooling was required in the day time. In Zone V, for January, the lowest temperature was higher than that of the lower temperature limit. Thus, it was concluded as only four months were suitable for cultivating tomato in the greenhouse, and the culture period was indeed too short for this crop.

The optimum temperatures of cucumber were combined in a climograph, as shown in Figure 4b. From Figure 4b, it is explained that two months in Zone IV were of optimum condition and three months in zone V required heating at nighttime. However, night temperature was higher than the limit growing temperature to grow cucumbers.

There were six months located in Zones I and II, as shown in Figure 4c. Cooling at night by conditioners was an impractical method for greenhouse production. The other six months, from November to April of the next year, were suitable to cultivate melon. However, the suitable time for cucumber and melon was overlapped, and thus, the rotation culture was observed to be difficult in Tainan, Taiwan. So, only one crop was suited to cultivate in the greenhouse by utilizing the greenhouse only half-year.

3.2.3. Miyazaki-shi, Japan

Despite the weather of Miyazaki-shi area being classified as subtropical, the results indicate that the temperature distribution was different to that of Tainan and Yulin, Taiwan. The combination of climographs of Miyazaki-shi, Japan and the range of optimum temperature for three fruit vegetables—tomato, cucumber, and melon—are displayed in Figure 5.
(a) Tomato

(b) Cucumber
Figure 5. The combination of climographs of Miyazaki-shi, Japan and the range of optimum temperatures for three fruit vegetables: (a) Tomato; (b) cucumber; (c) melon.

The results indicate that for tomato (Figure 5a), cooling at night was required for three months and heating in the day and at night was required for most of the months. The observed night temperature was lower than the growing limitation, and hence, heating was absolutely necessary in some months.

For cucumber, cooling in the day and at night was required for two months (July and August), and the heating at night was necessary for several months, as shown in Figure 5b. The coordinate points of four months (June to September) were located in the optimum zone. In the other months, heating was required in the day and at night. Based on these observations, it was concluded that only four months (from June to September) were suitable to grow melon, as shown in Figure 5c.

All year round culture of these species was only possible with various controlling equipment. It was stated that, for three species grown in the greenhouse located in Miyazaki-shi, Japan, heating was essential and it was difficult to cultivate tomato without heating and cooling. The other two species could grow well in the greenhouse in good ventilation by keeping the internal air temperature closer to the outside air. However, in this case, the heating cost, especially at night, remained a challenge to balance the production plan.

3.3. Lowland in Tropical

3.3.1. Ho Chi Minh, Vietnam

The combination of climographs of mean temperature of Ho Chi Minh, Vietnam and the optimum ranges of cucumber and melon are given in Figure 6.
In this case, high temperature and humidity were observed as the typical tropical weather. It was believed to be the worst climate to cultivate both tomato and cucumber. The observation conveyed that the cooling was required in the day and at nighttime for cucumber. To consider melon cultivation, cooling of the air of the greenhouse in the day and at night was required for three months (March, April, and May). Zone II comprised four months. However, the night observed temperature was deviated only a little bit from the optimum temperature (24 °C). Melon was found to be the suitable crop in the greenhouse and it was concluded that nine months was considered as the appropriate culture period. Adequate ventilation to keep the inside air temperature closer to the outside air temperature was found to be essential.

3.3.2. Los Banos, Philippines

The combination of climographs of mean temperature of Los Banos, Philippines and the optimum ranges of cucumber and melon are shown in Figure 7. Due to the inappropriate temperature at nighttime, both species—tomato and cucumber—could not be grown in the greenhouse. Most of the time within the year was suitable for melon. In April and May, the day temperature was observed to be a little higher and might be improved by misting. Good ventilation ability was the key factor to ensure the inside air temperature to close to the ambient air temperature.
Figure 7. The combination of climographs of mean temperature of Los Banos, Philippines and the optimum ranges of cucumber and melon.

3.4. High Land in Tropical

3.4.1. Da Lat, Vietnam

The combination of climographs of mean temperature of Da Lat, Vietnam and the optimum temperature ranges of tomato and cucumber are shown in Figure 8. In most of the months, the day temperature was found to be optimum for cucumber and tomato.

Figure 8. The combination of climographs of mean temperature of Da Lat, Vietnam and the optimum ranges of tomato and cucumber.
The night temperature in all months was comparatively higher than that of the limit of grow activity. So, the key function of the greenhouse in this area was to keep the inside temperature warmer than the outside air temperature, and to maintain not exceeding the optimum high temperature. The adjustable ventilation device was suitable for greenhouses in this area. It was expected that if the heating device could be installed to increase the night temperature, the yields and quality of cucumber and tomato might be improved significantly. The climate characteristics of the Da Lat area were appropriate for most of the temperate vegetables.

The weather characteristics for melon located in Zone VI (not shown in Figure) indicate that long-term heating was required in the day and at night. The cost of heating equipment and energy increases the production cost and restricts its market competitiveness.

3.4.2. Baguio, Philippines

The combination of climographs of mean temperature of Baguio, Philippines and the optimum temperature ranges of tomato and cucumber are given in Figure 9. The results indicate that, similar to the Da Lat area, cucumber, tomato, and other temperate vegetables were suitable to cultivate in this area. On the other hand, melon and other thermophile vegetables were not suitable to grow in this area.

![Figure 9. The combination of climographs of mean temperature of Baguio, Philippines and the optimum ranges of tomato and cucumber.](image)

3.4.3. Cameron, Malaysia

Figure 10 shows the combination of climographs of mean temperature of Cameron, Malaysia and the optimum temperature ranges of tomato and cucumber. The adequate conditions of the greenhouse plan were similar to Da Lat, Vietnam and Baguio, Philippines. The temperate vegetables were suitable to cultivate in this high land. Sufficient ventilation in the day and suitable heating at night were the key factors for greenhouse production.
4. Discussion

In this study, the climograph was obtained by plotting the mean minimum monthly temperature on the Y-axis and mean maximum monthly temperature on the X-axis. The optimum temperature ranges of three fruit vegetables were combined in these climographs. As mentioned already, the basic considerations, with the help of the greenhouse microclimate model, are listed as follows:

1. The way of cooling the temperature at night was carried out by using conditioners. However, the cost of equipment and energy were high and the economic benefit was low.
2. In order to reduce the internal air temperature in the day, the evaporative cooling method was applied. However, the high humidity in subtropical and topical areas restricted its cooling ability.
3. Ventilation rate played a major role in controlling the internal air temperature in the day. Sufficient ventilation helped to maintain the internal air temperature close to the ambient air temperature.
4. In this study, the night temperature of locations seemed to be higher than that of the limit temperature for the required activity of crops. It was suggested that the heating at night might increase the yields and enhance the quality for greenhouse production in high lands.
5. Solar radiation was not a limiting factor in these areas. Shading nets were considered as basic and indispensable devices.

Seven locations in subtropical areas were selected to demonstrate the application of a climograph for the cultivation of species. The rotation of temperate (tomato or cucumber) and thermophile (melon) plants in Yulin, Taiwan was proposed according to the information of the climograph.

In Tainan, Taiwan, the high night temperature at night in summer could prohibit the growth of melon in the greenhouse. Cucumber and melon were found as suitable crops for cultivation in one season. Hence, the greenhouse could not be used all year round.

In Miyazaki-shi, Japan, the heating at night was essential for several months for fruit vegetables, which could consume a lot of energy consumption.

The results of the assessment of the climographs of two locations in low land areas (Ho Chi Minh, Vietnam and Los Banos, Philippines) indicate that the thermophile crop, melon, was the only crop that could be cultivated in the greenhouse by considering the information of the climograph.
Three locations in high land areas (Da Lat, Vietnam, Baguio, Philippines, and Cameron, Malaysia) were selected to illustrate the suitability of the cultivation of the temperate vegetables; they were suited to cultivate in these areas. Heating at nighttime could enhance the yields and quality.

The controlling of the day temperature of the greenhouse in the day was suggested as an important key factor for subtropical and tropical vegetables. Sufficient ventilation rate played a major role in releasing the temperature increase of internal air due to the greenhouse effect [3,4,6].

Climographs have been used by researchers. Most of the reports have concerned the relationship between the mean radiation and mean monthly air temperature [10–17]. Climographs obtained by plotting the mean monthly minimum and maximum air temperature were only reported by Kittas [12] and Zabeltitz [10]. However, in their reports, the temperate and Mediterranean region were studied and the solar radiation was assumed as the limiting factor for the cultivation of crops. The required conditions of crops were not mentioned in these papers.

The novelty technique developed in this study was to define the climograph by plotting the mean monthly minimum air temperature versus the mean monthly maximum air temperature. With the knowledge of the temperature requirement, three species—tomato, cucumber, and melon—at different locations in subtropical and tropical climates were selected to illustrate the application of this climograph. Suitable species and cultivation period were achieved using a combination of climographs and the optimum temperature ranges of species.

5. Conclusions

The applicability of climographs for the greenhouse plan of subtropical and tropical regions was highlighted in this study. The climograph was defined as the incorporated mean of minimum and maximum monthly temperature and the range of the optimum day and night temperature of crops. This technique was used to build a plan for greenhouse crop cultivation. Three species at different locations in subtropical and tropical climates were selected in order to demonstrate the application of climographs. The suitable species and cultivation period were concluded by using the combination of climographs and the optimum ranges of cultivation temperatures. The results in three locations of high land areas indicate that all temperate vegetables could be cultivated successfully in these areas. Based on the observation, it was suggested that heating at nighttime could enhance the yield and quality. The major advantage of this technique was that this method can also be used for other species at different locations for the greenhouse production plan. An analysis of reported work indicates that the development of economical and effective technology suitable to local climatic conditions was inevitable to lift up the greenhouse industry. The reviewed data in this study could suggest that a ventilated greenhouse was suitable for crop cultivation throughout the year in tropical and subtropical regions. The method proposed in this study could also be applied to other species at different locations in subtropical and tropical climates for the greenhouse production plan.

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References


