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Prediction of the Energy Consumption for Indoor Strawberry Cultivation in a Tropical Climate

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Abstract: This article addresses the lack of information for predicting the energy consumption of strawberry plantations inside plant factories located in tropical climate regions. This study aims to investigate the energy consumption of the cultivation of strawberries in the controlled environment room and to develop a TRNSYS computer model for the controlled environment room. Experiments were conducted in a 25 m3 controlled environment room. There are 180 strawberry trees inside the room. Light Emitting Diode (LED) grow light substitutes for natural sunlight. An air conditioner was used to regulate the indoor air condition. A computer model was developed using TRNSYS (TRaNsientSYStem simulation tool) and was validated using the collected data. There are three main components of the room heat load: transmission, lighting, and evapotranspiration. The lighting heat load shares more than 96% of the total heat load — the evapotranspiration load increases when the LED turns on. However, the lighting consumes only about 36% of total electricity consumption, while the air conditioner consumes 64%. Most of the electricity is used during the runner stage. Electricity consumption can be saved by 40% if the runners are grown outside the plant factory. Therefore, the high heat load is a feature in the plant factory. In this study, the lighting heat load is the most significant parameter. The strawberry light intensity requirement is the high lighting heat load. Consequently, the electricity for the air conditioner becomes high since the air conditioner removes the generated heat from the high light intensity. Therefore, the air conditioner electricity consumption is enormous in this study. Moreover, the required lighting intensity, photoperiod, and low air temperature factors affect electricity consumption. Therefore, the results from this study could provide strategies for energy cost reduction and plantation management for plant factories cultivation.

Keywords: controlled environment room, strawberry, TRNSYS, plant factory, energy consumption.

热带气候下室内草莓栽培能耗预测

摘要：本文解决了缺乏信息来预测位于热带气候地区的植物工厂内的草莓种植园的能源消耗。本研究旨在调查可控环境室种植草莓的能耗，并开发可控环境室瞬态系统仿真工具计算机模型。实验在25 立方米可控环境房间内进行。房间里有180棵草莓树。发光二极管生长光替代自然阳光。空调被用来调节室内空气状况。使用瞬态系统仿真工具开发了一个计算机模型，并使用收集的数据进行了验证。室内热负荷的三个主要组成部分：传输、照明和蒸散。照明热负荷占总热负荷的96%以上——当发光二极管开启时，蒸散负荷增加。然而，照明仅消耗总用电量的36%左右，而空调消耗64%。大部分电力用于跑步者阶段。如果跑步者在植物工厂外种植，则可节省40%的电力消耗。因此，高热负荷是植物工厂的一个特点。在这项研究中，照明热负荷是最重要的参数。草莓光照强度要求是高光照热负荷。因此，由于空调从高光强度中去除所产生的热量，所以空调的电力变高。因此，本研究的空调耗电量是巨大的。此外，所需的光照强度、光周期和低温等因素也会影响电力消耗。因此，本研究

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结果可为植物工厂种植的能源成本降低和种植管理提供策略。

关键词：**可控**环境室、**草莓**、瞬态系统、**植物工厂**、**能源消耗**。

1. Introduction

Over the past few decades, unusual climate changes worldwide have been the primary source of problems for growing crops in open fields [1]. Unpredicted weather and insects affect the crops' quality and quantity. For this reason, greenhouse technologies for cultivating crops are usually used to mitigate the local climate, hence increasing quality and quantity [2]. Greenhouse evolved from simply covered plastic rows to advanced and sophisticated controlled environment greenhouses [3]. However, the simple plastic cover greenhouse can protect crops from raindrops during the rainy season and frozen water drops in winter. It can also increase inside air temperature. Controlling temperature and humidity is impossible in a simple greenhouse. Additional insect nets may be installed to protect crops from unwanted insects. The most advanced and sophisticated greenhouse can protect crops from insect and environmental changes. Furthermore, it can create the environment inside the greenhouse to suit each specific crop requirement.

Strawberry can be grown in open fields and greenhouses. Generally, the open-field cultivation technique is suitable when weather conditions are balanced with strawberry nature, whereas the greenhouse plantation is favored to avoid unpredictable weather conditions. Strawberry cultivation in the plastic cover greenhouse is common in northern Europe [4]. However, there exist challenges to plastic greenhouse cultivation of strawberries in tropical climate regions where the ambient air temperature is ordinarily high [4,5]. Thus, researchers introduce one form of controlled environment greenhouse known as a plant factory (also called "closed plant production system") [6]. One of the advantages of the plantation in a controlled environment greenhouse is that it can alleviate the external environmental conditions, promoting complete control of the indoor environment for the plantation.

Three main factors influence strawberry growth: ambient air temperature, sunlight duration or photoperiod (the sunshine hour within a day), and sunlight intensity [7]. The warm air temperature and cool air temperature support strawberry vegetative growth and initiate flower buds [7]. The photoperiod should be enough under the strawberry growth stage and photoperiod hours [7]. If the light intensity is too high, it can inhibit strawberry growth [8]. Excessive ambient temperature, harsh sunlight hours, and (low or high) light intensity caused by unstable weather conditions could induce a reduction in strawberry growth. However, these unpredictable weather conditions can be avoided by creating a suitable climate for strawberry plants. Thus, a controlled environment room is an alternative approach where the preferable air temperature, photoperiod, and light intensity can be provided for the plantation of strawberries. Nonetheless, vegetative production in closed systems, such as plant factories and vertical farming, is still an issue for energy management [9]. K. Harbick and L.D. Albright compared the annual energy consumption in plant factories and greenhouse by simulation in which the assumed crop is lettuce [10]. Graamans et al. calculated the resource requirements for lettuce production in greenhouses and plant factories and examined how these requirements are influenced by external climate conditions [11]. The above researchers claimed that energy consumption is significantly higher in the plant factory environment compared to the greenhouse.

The indoor strawberry plantation technique is not broadly investigated, specifically in tropical climates. Therefore, this new plantation technology requires higher energy consumption than the traditional method. Furthermore, previous research only investigated the technical feasibility of the plant factory. Thus, minor works exist on the associated operating costs. This study aims to estimate the energy consumption of growing strawberries in a plant factory. First, experiments were conducted in a small testing room to investigate the relationship of associated variables. Then, a computer model was developed and validated using TRNSYS to estimate energy consumption. Results from this study were used to provide strategies for energy cost reduction and plantation management. The proposed evaluation method could also be applied for valuable fruits and vegetative cultivation.

2. Methodology

2.1. Experimental Room Setup

The experimental room was at Chiang Mai University, Thailand. The room was constructed inside a building on the ground floor. Fig. 1(a) shows The overview of the control room Fig.1layout. The room floor area was 11.36 m2. The height of the room is 2.2 m. The entire room was built up with 5-inch thick, opaque polystyrene (PS) foam insulation panel except for one side of the room. One side was made of double glass for viewing from the outside. The thermal conductivity of polystyrene foam was 0.023 W/m-K. Four vertical shelves were placed parallel inside the room to house strawberry trees. Each shelf has three levels. Each level of the shelves can grow 15 strawberry trees, as shown in Fig.1

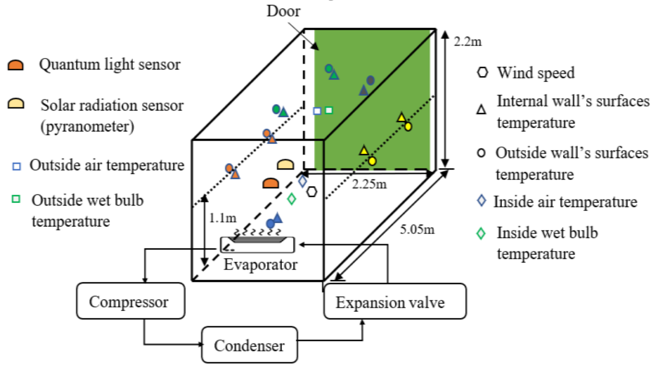
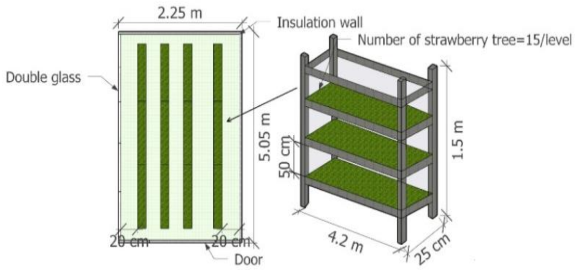


Fig.2(b). There were 180 strawberry trees inside the controlled environment room, as shown in Fig.1 (c).



Top view (a) Vertical shelf (b)

(c)

Fig.1 1 Experimental room: (a) shelf layout, (b) vertical shelf, and (c) actual picture inside the room

LED light bulbs were used in the controlled environment room to substitute for sunlight. There were 72 LED light bulbs inside the controlled environment room (2 LED bulbs for five strawberry plants). The energy demand from each LED light bulb is 75 W. Therefore, the total power from the lighting system is 5.4 kW. Additionally, an air conditioner (3-ton refrigeration) provides suitable air temperature and humidity inside the control room.

Strawberry season in the open field (outdoor cultivation) commonly takes more than six months. The season starts in June in the northern hemisphere, and the berries are available from December to February. Strawberry growth has a strong relationship with ambient temperature, lighting hours, and lighting intensity [7]. The nighttime air temperature of the strawberry is usually lower than the daytime air temperature. Therefore, a lower air temperature (10−15°C) is required for flower and fruit induction. A photoperiod of around 10-12 hours per day is desirable for the runner stage, whereas an 8–10 hours per day photoperiod is preferable for the rest of the stages [7]. Thus, to simulate the environmental condition requirement for strawberries, the schedule for the air conditioner and the LED grow light is shown in Table 1.

Table 1 Timetable for temperature regulation and LED grow light for the experiment and simulation [7].

Strawberry growth stages	**Time**	**The room setting air temp (°C)**	**Lighting**
Runner	00:00–08:00 08:00–18:00 18:00–24:00	25 30 25	OFF ON OFF
Floral initiation	00:00–08:00 08:00–16:00 16:00–24:00	18 25 18	OFF ON OFF
Flowering and fruiting	00:00–08:00 08:00–16:00 16:00–24:00	15 25 15	OFF ON OFF

2.2. Data collection

The positions of the measuring devices are presented inFig.2. Interior air temperature, relative humidity, wind speed, solar radiation, and Photosynthetic Photon Flux Density(PPFD) were measured. The wind speed is measured with an anemometer. T-type thermocouples were used to measure the air temperature of the controlled room. Solar radiation and Photosynthetically Active Radiation (PAR) were measured using a pyranometer and quantum light sensor.

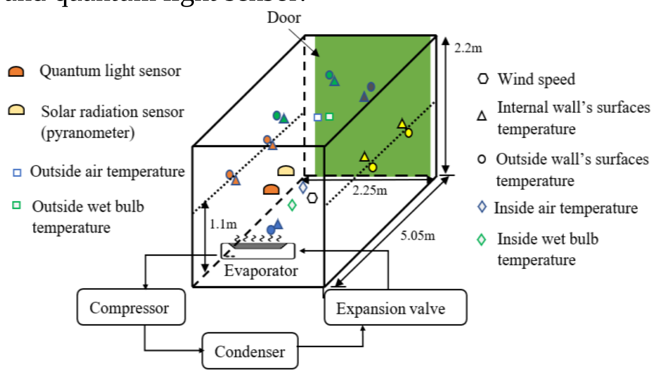


Fig.2 The schematic layout of measuring points in the controlled environment room

The solar radiation and quantum light sensors are located near the strawberry trees to monitor the strawberry trees' environment. All controlled environment room data were collected at a minute interval. Moreover, the portable memory Hioki logger collects the inside air temperature. Specware WatchDog 2000 series data logger was set up to PAR and solar radiation. The specifications of the equipment used are shown in Table 2.

Table 2 Specification of the measuring instruments

Measuring parameters	Measuring instrument	Technical parameter
Wall surface temperature Ambient temperature Inside room temperature Inside wet-bulb temperature Wet-bulb temperature	T-type thermocouple	Temperature ranges: -250 °C–350 °C, tolerance: ±1°C
Solar radiation	Silicon pyranometer sensor	Measurement range: 1–1,250 W/m2, accuracy ±5%
Light radiation	Quantum light sensor	Measurement range: 0–2,500 µmol/m2s, accuracy ±5%
Wind speed	Digital anemometer	Measurement range: 0.4 ~ 25.0 m/s

2.3. Heat Transfer Characteristics

Heat transfer to the air inside the strawberry grows room consists of external and internal heat gains, as shown inFig.3. The external heat gains are from the heat transfer through the building envelope, such as walls, roof, floor, doors, and windows. The controlled environment room is well insulated and has an airtight structure. So, the infiltration and ventilation heat loads are neglected. The internal heat gains are due to heat generated inside the grow room from the LED light bulbs and evapotranspiration of the strawberry trees.

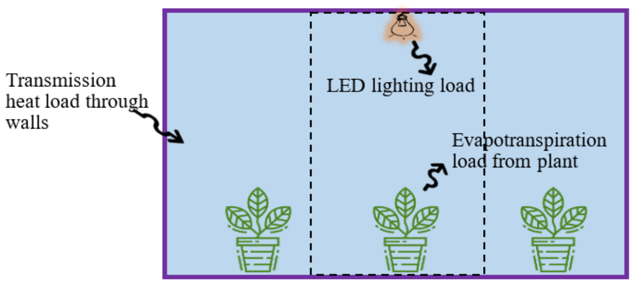


Fig.3 3 Illustration of the heat transfer process

Thus, the total heat load of the strawberry grows room is described using the following equation:

$$Q_{total} = Q_t + Q_{lighting} + Q_{Et} \quad (1)$$

2.3.1. External Heat Gains

The temperature difference between outdoor and indoor air is the driving force for the transmission heat load. Heat usually flows from the high temperature to low temperature media [12]. In this study, transmission heat transfer occurs by conduction through the wall and ceiling of the controlled environment room. The transmission heat transfer can be expressed using the following equation:

$$Q_t = UA\Delta T \quad (2)$$

where U is the overall heat transfer coefficient (W/m^2-K), A is the area of the wall's surface (m^2) and ΔT is the temperature difference between inside and outside of the room (°C).

2.1.1. Internal Heat Gains

In this study, internal heat gains are from the LED light bulbs and evapotranspiration from strawberry plants. The electricity consumption can help calculate heat gain from the LED light bulbs. Although the electricity supplied to the LED is converted to heat and light, all the energy from electricity eventually adds to the controlled volume. Thus, the heat gain from LED is expressed in the following equation:

$$Q_{lighting} = no.of\ LEDs \times W_{LED} \quad (3)$$

Another source of internal heat gain in this study is the evapotranspiration from the strawberry plants. Evapotranspiration is the combination of two processes: evaporation and transpiration. Evaporation is the loss of water from the soil surface, whereas transpiration is the loss of water from the plant leaves [13]. These two processes co-occur; therefore, it is difficult to distinguish between two processes. For the indoor condition where the wind speed is less than 1 m/s, the evapotranspiration rate *(ET)* is calculated using the Stanghellini model, as shown in Equation 4. Note that the crop coefficients (K_c) of strawberries for the initial stage, mid-season stage, and at the end of the season stage are 0.4, 0.85, and 0.75, respectively [13].

$$ET = 2LAI\,\frac{1}{\lambda}\,\frac{\Delta\,(R_n - G) + K_t \frac{VPD.\rho.c_p}{r_a}}{\Delta + \gamma\,(1 + \frac{r_c}{r_a})} \quad (4)$$

where λ is the latent heat of vaporization (MJ/kg), R_n is the net radiation (MJ/m^{2}hr), G is the soil heat flux (MJ/m^2-hr), K_t is the unit conversion (86,400, s/day for *ET* in mm/day; 3,600, s/hr for *ET* in mm/hr), $VPD = es - ea$ is the vapor pressure deficit of the air (kPa), *es* is the saturation vapor pressure (kPa), *ea* is the actual vapor pressure (kPa), ρ is the air density (kg/m^3), c_p is the specific heat capacity of air (MJ/kg-K), r_a is the aerodynamic constant (s/m), r_c is the canopy constant (s/m), Δ is the slope of saturation vapor pressure curve at an air temperature in kPa/K, γ is the psychrometric constant, and *LAI* is the plant leaf area index (dimensionless). The leaf area index (LAI) is the ratio of the leaf area of the plant canopy (m^2) to the area of the soil (m^2) under it. The size of the leaf is measured with a ruler. The LAI can be calculated using the following equation:

$$\text{LAI} = \frac{\text{leaf area}(m^2)}{\text{soil area underneath}(m^2)} \tag{5}$$

The heat gain from the evapotranspiration is determined as follows:

$$Q_{Et} = \frac{ET\lambda\rho A_p}{1000} \tag{6}$$

where A_p is the plant surface area (m^2).

2.4. Electricity Consumption

There are two main pieces of equipment for electricity consumption in the strawberry grow room: the LED light bulbs and the air conditioner. The electricity consumption of the LED light bulbs is described in Equation 3. The electricity consumption of the air conditioner can be estimated from the calculated total heat gains and the coefficient of performance (COP) of the air conditioner used as follows:

$$E_{AC} = \frac{Q_{total}}{COP} \tag{7}$$

The total electricity consumption of the strawberry grow room can then be calculated as follows:

$$E_{total} = E_{AC} + Q_{lighting} \tag{8}$$

2.5. Modelling of Cultivation Room in TRNSYS

The schematic diagram of the developed TRNSYS model is presented inFig.4.Type 56 (multizone building component) was used to model the controlled environment room. This component models the thermal behavior of a building [14]. Since the strawberry cultivation room was a single space, the building is assumed as a single zone. Thus, all the walls were employed with "outwall." In addition, the same physical opaque insulation material and thickness were inserted for the wall.

It should be noted that the convective heat transfer coefficient of the inner and outer wall was assumed to be 5.76 kJ/hr-m^2-K and 11 kJ/hr-m^2-K, respectively. All the inputs, such as the cooling system, lighting system, and evapotranspiration submodel, were connected before running the simulation. Furthermore, the attachment of solar radiation to all the room's surfaces is disconnected as the room is located inside the building. The heat gain from the evapotranspiration is calculated separately using user-defined equations. The calculated results are supplied to Type 56.

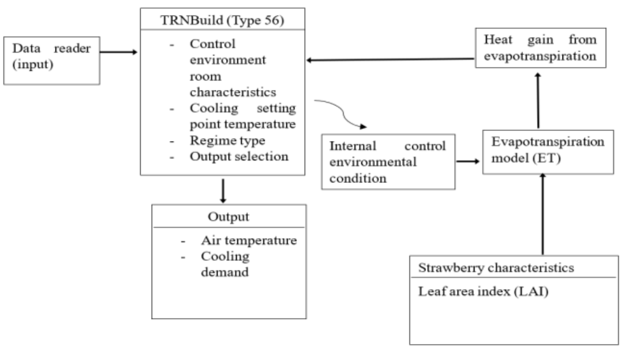


Fig.4 Flowchart of the TRNSYS controlled environment room

2.6. Validation of the TRNSYS Model

The TRNSYS, a controlled environment room model, was validated and implemented with experimental data. The computed internal air temperature of the TRNSYS controlled environment room model, was compared with the internal air temperature obtained experimentally. Root mean square error (RMSE) and relative root mean square error (rRMSE) were used as statistical analysis methods. RMSE represents the standard deviation of the difference between measured and computed values, while rRMSE is another indicator of the accuracy of the measured and computed values. The model is in good condition if the rRMSE value is <10%, fair if it is <20%, and poor if it is >30%. The mathematical expressions are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_{ia,exp} - T_{ia,sim})}{n}} \tag{9}$$

$$rRMSE = \frac{100}{T_{ia,mean}} \times \sqrt{\frac{\sum_{i=1}^{n}(T_{ia,exp} - T_{ia,sim})}{n}} \tag{10}$$

where $T_{ia,exp}$ is the internal air temperature from the experiment (K), $T_{ia,sim}$ is the internal air temperature obtained from the simulation (K), $T_{ia,mean}$ is the mean of the experimental internal air temperature (K), and n is the number of measurements.

3. Results and Discussion

3.1. The Environmental Conditions of the Strawberry Grow Room

The indoor environment condition is vital for the cultivational room. The experimentally collected inside room air temperature (T_{amb}), ambient air temperature (T_{ia}), and inside (ω_{in}) and outside (ω_{out}) humidity ratio of the strawberry grow room are shown in Fig.5. The outside humidity ratio is 0.02 and 0.04 kg$_{water}$/kg$_{dry\ air}$. The humidity ratio increases proportionally to the ambient temperature. On the other hand, the inside humidity is almost constant, changing in a small range (0.005 to 0.015 kg$_{water}$/kg$_{dry\ air}$). That indicates that the air conditioner can remove additional moisture from the air inside the room. The ambient temperature range is between 25°C and 35°C. The inside air temperature is approximately 17°C during nighttime and 27°C during daytime. Therefore, the inside air temperature range is according to the temperature schedule.

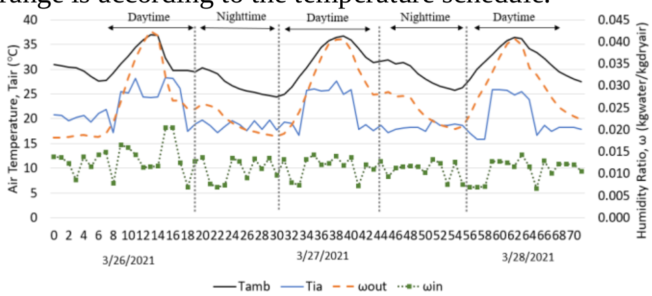


Fig.5 5 Inside and outside air temperature profile of controlled environment room and outside humidity ratio

The air's relative humidity (RH) inside the room is around 60%–70%, suitable for avoiding fungal disease breakouts [6]. However, high RH (up to 90%) can result in fungal diseases.

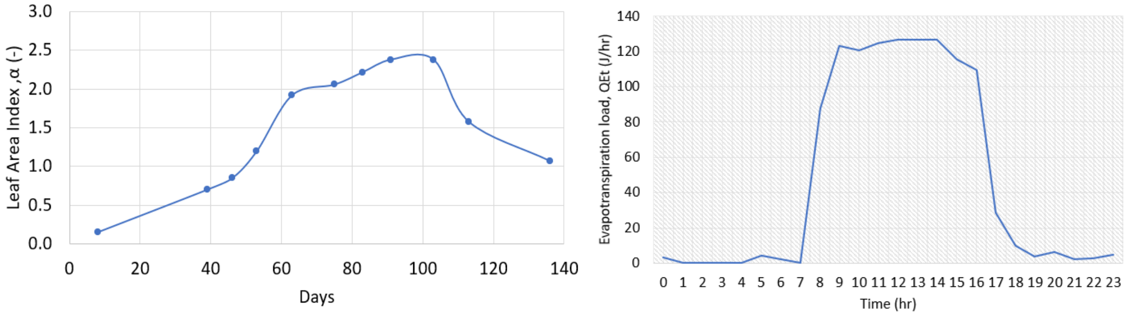
3.2. Heat Load of the Controlled Environment Room

The LAI is one of the parameters that affect the evapotranspiration load. The LAI value of a strawberry plant is presented in Fig.6(a). In the figure, the LAI value steadily increases from the initial stage of the strawberry plant. After 50 days, where LAI equals 1.0, LAI increases sharply for about ten days. Then, LAI reaches the maximum value of 2.37 at 100 days. Later, the LAI value falls during the end season. LAI changes throughout the season, peaking just before or at flowering. The LAI nature is a bell-shaped curve for most plants [13]. The strawberry LAI range varies between the value of 1 and 2.5 under the protected cultivation conditions [15]. The leaf numbers and the leaf area dominated the LAI value. Leaf numbers and leaf area can either increase or decrease based on the strawberry growth period.

On the other hand, these two parameters might differ slightly for each strawberry plant. Therefore, it might affect the LAI value of each strawberry plant. However, in this study, the LAI values for every strawberry plant were assumed to be the same.

Based on the LAI, the evapotranspiration load can be estimated. The higher the LAI value, the higher the evapotranspiration flux [16]. At the peak of LAI, that is 2.37, the evapotranspiration load of one strawberry plant for the day can be seen in Fig.6(b). The evapotranspiration load of a strawberry plant was estimated according to Equation 6. Moreover, crop evapotranspiration is influenced by many factors, including LAI value (crop growth stage) and climatic conditions (temperature, humidity, wind, and light intensity) [10]. The crop evapotranspiration rate causes the evapotranspiration load. It can be seen that the evapotranspiration load is exceptionally high (about 120 J/hr) when the LED grow light is turned on.

Conversely, the evapotranspiration load is low when the lighting is off. Therefore, it implied that the evapotranspiration rate is proportional to the amount of radiation obtained [10]. That also indicated that the high evapotranspiration load is associated with the high light intensity that the plants received.



(a) (b)

Fig.6 (a) LAI value ranges of a strawberry plant; (b) the evapotranspiration load profile of one strawberry plant for a day

Strawberry plant runner growth and fruit production require a minimum DLI of 17 mol/m^{2}day. The optimal DLI level for all stages is 20 mol/m^{2}day [17].

As mentioned earlier, the total heat load is composed of the transmission load (Q_t), the lighting load ($Q_{lighting}$), and the evapotranspiration load (Q_{Et}). The hourly total heat load to be removed from the strawberry grow room is illustrated in Fig.7. It can be noticed that the lighting load shares the most significant portion, about 96% of the total daily heat load. The other two heat loads are almost insignificant compared to the lighting load. When the LED lighting is provided, the total heat load peaks at approximately 20 MJ/hr.

The evapotranspiration heat load of 180 strawberry plants slightly increased when the LED lighting was turned on (8 am– 4 pm). The average evapotranspiration heat load is 0.02 MJ/hr.

The transmission heat load fluctuated throughout the day. In the early morning, the transmission heat load is low (0.13 MJ/hr) because the outside and inside air temperature difference is about 7 degrees. However, the transmission heat load is high during the evening (0.35 MJ/hr) due to the significant disparity between the external and internal air temperatures, about 20 degrees. That confirms that the exterior climate has a low impact than the lighting load [9]. Moreover, Chaichana et al. stated in their study of closed cultivation chamber that the lighting load is the most dominant of total heat load [18].

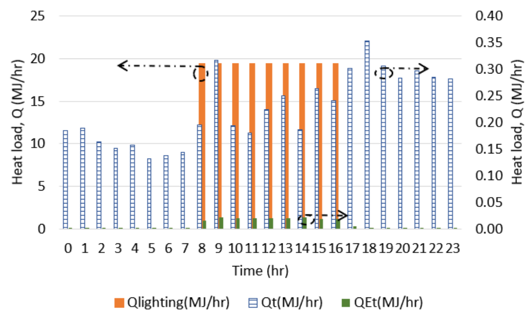
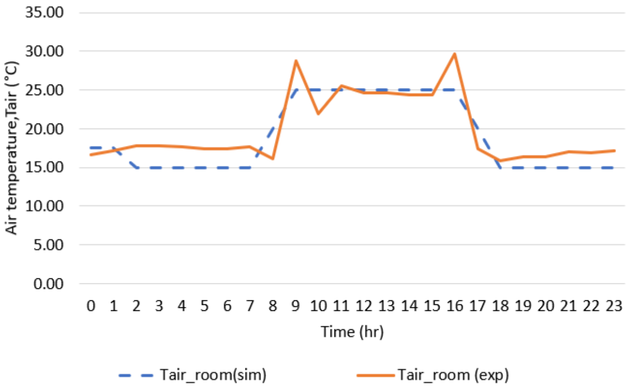


Fig.7 Typical total heat load over 24 hours inside the controlled environment

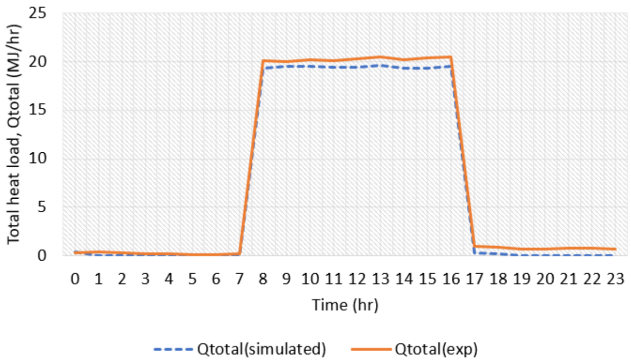
3.3. Validation of the Developed TRNSYS Model

The TRNSYS model was applied for further analysis and was developed and validated. For validating the TRNSYS model, the computed room air temperature from the model and the experimental room air temperature were compared, as shown in Fig. 8(a). The validation was carried out over the maximum LAI day. The statistical analysis results indicate 2.3°C (RMSE) and 0.79% (rRMSE) values, respectively. The rRMSE value is considered to be in the acceptable range (<10%). Several studies regarding the greenhouse simulation model described that an rRMSE value of less than 10% is reasonable [19]. Hence, the developed simulation model in this study is accurate enough to simulate the controlled environment room condition.

For ensuring the validation of the model, the hourly heat load of the experiment and simulation of the TRNSYS controlled environment room were compared, as shown in Fig. 8(b). The result highlights a good agreement between the simulated and experimented hourly heat load, with rRMSE at 9.2%. Therefore, the developed TRNSYS model is applied to predict the heat load of the controlled environment room for the strawberry cultivation period.



(a)



(b)

Fig. 8 (a) Validation of inside air temperature profiles from measurement and simulation. (b) The comparison of the simulated and experimental heat load

3.4. Total Heat Load Over One-Season Cultivation

After validation of the model, it is used for further analysis. For simulating the whole period of strawberry cultivation, the corresponding schedule for each strawberry growth stage is adapted to meet the requirements of strawberry conditions (Table 1).

It is necessary to address the heat load of the controlled environment room to be able to control the indoor climate [9]. Fig.9 presents the calculated total heat load for one crop cycle of a strawberry plantation in a controlled environment room. The pie chart comprises four stages of strawberry development: runner, floral initiation, flowering, and fruiting. The total heat load to be eliminated from the closed room was about 40 GJ for all stages.

The largest share of the total energy consumption was the runner stage, 14 GJ (35%). Long daily photoperiod is the main reason for the highest consumption. A minor proportion was observed for flowering (5 GJ, 13%), while the rest stages (floral initiation and fruiting) were about 10 GJ (26%) and 10 GJ (26%), respectively. The period for lighting and strawberry stage duration (i.e., the months it takes) would possibly be the reason for each strawberry growth stage's net heat load difference. Electricity use can be estimated based on this total heat load [11].

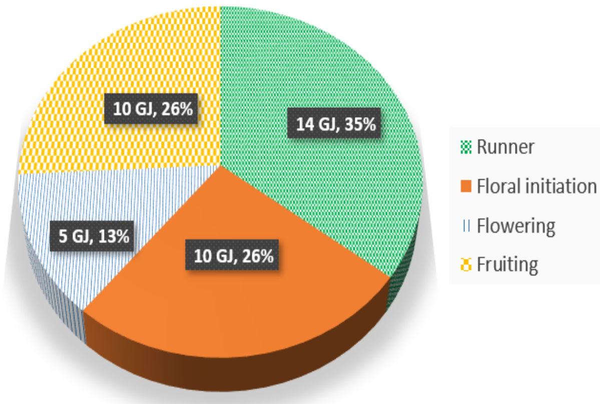


Fig.9 Estimated total heat load of each strawberry growth stage

3.5. Electricity Consumption

The total electricity consumption of the strawberry grow room during one crop cycle was calculated as shown inFig. 10. This study found that the air conditioner consumed more electricity (64%) than LED lighting (36%). This result does not agree with Weidner et al. [20]. In the mentioned study, year-round LED electric usage is more significant than other plant factory applications. Tomatoes, broccoli, bell pepper, lettuce, spinach, and summer squash were grown in their plant factory. These crops require less DLI compared with strawberries. In their work, the DLI requirement is around 13.6 mol/m^{2}day, whereas nearly 20 mol/m^{2}day is necessary for strawberries. In addition, they stated that the 14-hour photoperiod was supplied at night in the plant factory, which reduces the use of cooling during winter in the cold climate area.

Power consumption is due to the heat input from the LEDs. Since vertical shelves were used in both studies, installed LEDs power per cubic meter of the plant factory is compared. Lower power consumption LED

(30 W/m^3) is required in Weidner et al.'s [20] plant factory. On the other hand, the LEDs used in this study were 340 W/m^3. The high LED intensity released heat to the air-conditioned area inside the plant factory. Consequently, the energy used by air conditioning is increased.

In addition, the current study was performed in tropical areas in which the ambient temperature is relatively high, which contributes to the increased power consumption in the air conditioning system.

Electricity consumption during the runner stage is approximately 22 GJ/month, whereas it was only 12-13 GJ/month in the other stages. The total electricity used for one crop cycle of strawberry cultivation is about 107 GJ. The ratio of the electricity consumption of each stage from a runner, floral initiation, flowering, and fruiting is 40.0%, 25.5%, 13.0%, and 25.5%, respectively.

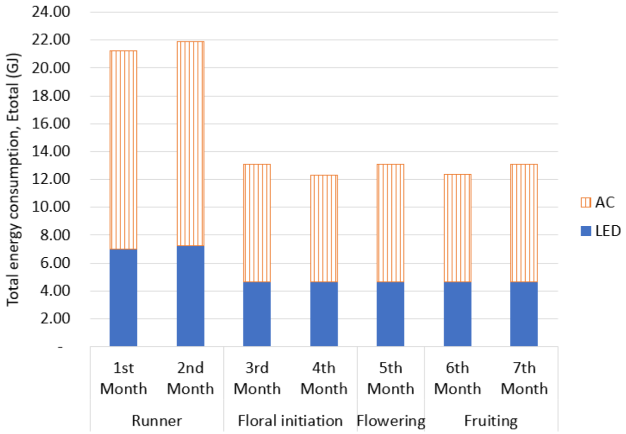


Fig. 10 The simulated monthly energy consumption of the controlled environment room.

The strawberry at the runner stage consumes more electricity than the other stages. A temperature of at least 22°C and a 12-hour or longer day length is required [21]. Both the air conditioner and LED light bulbs must work long hours. The air conditioner consumed a large amount of electricity to remove heat gain from the LED light bulbs. The days are warmer and more extended in tropical climate regions.

Since the runner stage of strawberry requires a daytime air temperature of about 30°C and a nighttime temperature of 25°C, it is possible to grow the strawberry in the outdoor environment. So, when the runner stage is grown outdoors, there is a 40% decrease in total energy consumption.

In Thailand, the average day and night temperatures slightly differ relative to months. In the winter months, the daytime and nighttime temperatures are around 30°C and 20°C in the winter months (December and January). The average day and night temperatures are stable from June to October, around 32°C and 25°C, respectively. In November, the daytime temperature remains the same, around 32°C, while the nighttime temperature slightly decreases to around 22°C. The hottest months in Thailand are March, April, and May, during which the day and night temperatures are 35°C and 25°C [22]. Thus, strawberry runner growing is possible from June to October in Thailand. When the runner plants are grown outdoors, energy consumption is reduced to 64 GJ (17.7 MWh) for one crop cycle cultivation.

Generally, strawberries' yield per strawberry plant varies depending upon the nurturing and weather conditions (i.e., air temperature, humidity, and lights). However, the average yield per strawberry plant is 150–400 grams using protected cultivation [6]. Thus, the maximum expected strawberry production of 72 kg could be achieved for 180 strawberry trees for one crop.

The specific energy consumption is the energy consumption per the output (kilogram) of the strawberry. The production of 1 kg of strawberry demands 246.8 kWh energy input. Graamans et al. reported that input of 247 kWh is required to produce a 1 kg dry weight of lettuce [11]. That proves that the plant factory requires a large amount of input energy.

4. Conclusions

This study investigated energy consumption for the strawberry plantation in the controlled environment room. The experiment was implemented in the controlled environment room. The TRNSYS controlled environment room model for strawberry cultivation was developed and validated. It was found that LED shares the highest (almost 96%) heat load. The runner stage requires the highest energy in the growth stages because it needs a more extended photoperiod. LED light consumed 36% of total energy consumption for the electricity consumption, while the air conditioner used 64%. Therefore, the energy demand in plant factories largely depends on LED lighting and cooling system applications. Since the runner stage can be grown at a slightly high ambient temperature, keeping the strawberry tree outdoors is possible. In this way, the total energy consumption is reduced by 40%.

The significance of this work is that it addresses the energy consumption for strawberry plantations in controlled environment rooms of tropical climate areas. The high heat load is featured in the plant factory. In this study, the lighting heat load is the most significant parameter among other heat loads. The daily light integral requirement for strawberries is 20 mol/m^{2}day. For meeting this requirement, a light intensity of around 340 W/m^3 is provided in the controlled environment room since the strawberries are grown on three levels of four vertical shelves. That becomes the reason for the high lighting heat load. It can be seen that the high heat load causes a large amount of energy input requirement.

Furthermore, the significant sources of electricity consumption are air conditioners and LED lighting in this study. Air conditioner consumes more electricity than LED lighting as the air conditioner remove the generated heat from the high light intensity. Besides, the ambient temperature is relatively high in those tropical areas. That is also one of the reasons for air conditioning electricity consumption. Therefore, the outcome of this study could provide essential information for potential energy cost reduction and plantation management under plant factories cultivation in tropical climate regions.

The limitation of this study is that the TRNSYS model is validated with the indoor controlled environment room. So, the model may require a few more additional analyses for validation when it comes to the outdoor plant factory. Furthermore, the experiment was implemented in tropical areas, and cooling is mainly in demand in the plant factories. Therefore, the plant factory in cold regions will require a heating system.

From the engineering perspective, energy consumption is one of the critical parameters in plant factories. Therefore, more research should be carried out from engineering to agricultural approaches to achieve economic plant growth in plant factories with LED lighting.

The proposed evaluation method for energy consumption could be applied to other plants sensitive to the ambient environment. Although the plant factory could allow for total climate control, the enormous energy demand for indoor plant cultivation is still an issue worldwide. It is worth noting that the plant factories are not designed to take the place of traditional farming. Instead, alternative farming is used to meet the high demand for fruits and vegetables.

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