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A Controlled Environment Agriculture Greenhouse for the Caribbean Region

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Abstract: *A prototype Controlled Environment Agriculture (CEA) greenhouse, designed to suit the climatic conditions of Trinidad and Tobago was constructed and tested alongside a non-controlled prototype greenhouse with natural ventilation. In the CEA greenhouse, fan and pad type evaporative cooling were used to reduce temperature; circulating air combined with natural ventilation to reduce the humidity and provide air movement. LED lights were used to extend day length and supplement photons delivered to the plants. The effect of these control measures, in the CEA greenhouse, was evaluated by measuring temperature and humidity variations. Plant growth parameters (plant height, stem diameter, and leaf surface area) were evaluated for the two greenhouses. The mean saturation effectiveness of the coconut fibre cooling pad material used in the evaporative cooler was found to be 25.3%. While, the temperature and relative humidity in the non-controlled greenhouse were higher; those in the CEA greenhouse were lower than the ambient temperature. The CEA greenhouse had significantly higher growth rates in all plant growth parameters (about two and a half times on the average) than the non-controlled greenhouse. The combination of blue LED light, evaporative cooling, and air circulation fans coupled with natural ventilation resulted in a significant increase in plant growth rates in the CEA greenhouse compared to the greenhouse with only natural ventilation as the weather control measure.*

Keywords: *Greenhouse, controlled, environment, Trinidad and Tobago*

1. Introduction

Trinidad and Tobago's food import bill is currently approximately US$ 0.6 billion per annum (Flemming et al., 2015). There is an urgent need to increase food production and reduce this expenditure. Protected agriculture has been proposed as one way to improve agricultural output, by protecting the crops from harsh weather conditions and pests and diseases (DeGannes et al., 2014). If well implemented and followed through intelligently, protected agriculture environment systems will aid in ensuring food security. According to Jensen and Malter (1995), protected agriculture (PA) is "the modification of the natural environment to achieve optimum plant growth." In general, greenhouses are environments which can be controlled to a much higher degree than outdoor fields. Greenhouses involve both passive and active ways of controlling the growing conditions inside the green house. Temperature, light, air humidity, water supply and carbon dioxide in the air can be regulated by the grower. In some modern greenhouses, even infestation by pests and pathogens can be restricted or prevented (EGTOP, 2013).

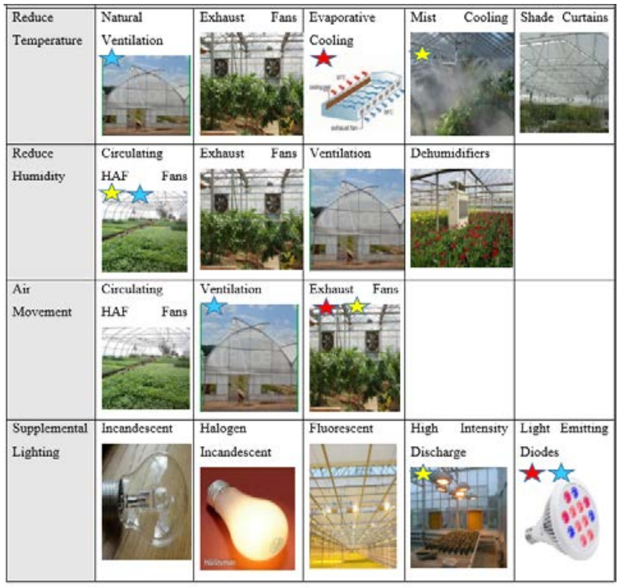
Martin et al. (2008) reported the rejuvenation in the use of greenhouses in Trinidad and Tobago following a collaborative approach by Agricultural Development Bank (ADB) and others to provide financial, marketing and technical support to persons interested in greenhouse crop production. Sahadeo et al. (2017) investigated the existing greenhouses, locally, regionally and internationally and designed and optimised a new system that could potentially be used in the Caribbean region. They found that while most designs could protect the crops from pests and diseases, temperature and humidity could be reduced only marginally by altering their designs, and changing some materials. They, however, found that to control the environmental parameters adequately, Controlled Environment Agriculture (CEA) greenhouses may be needed in the Caribbean. CEA is a subset of protected agriculture in which case all aspects of the natural environment are modified for maximum plant growth and economic return (Jensen and Malter, 1995; Albright and Langhans, 1996). Control may be imposed on air, temperature, light, water, humidity, carbon dioxide, plant nutrients alongside with complete climatic protection (Jenson and Malter, 1995). Tian et al. (2014) did a comprehensive assessment of a controlled growth environment in which they analysed the effect of environmental factors, like temperature, humidity, light, carbon dioxide and nutrients, on crop development. Their results showed that rapes grew very well; the growth period was short with higher quality yields than rapes grown in natural environment.

The major disadvantage of the CEA greenhouses is that they are very costly and may not be affordable to most local farmers. Before heavy investments are made, it is, therefore, necessary to construct a prototype CEA greenhouse and compare its performance locally (in terms of controlling temperature, humidity and other environmental factors) to a greenhouse with minimal means of weather control. Such an investigation will reveal whether the CEA greenhouses could lead to better crop yields and control of weather conditions. This paper starts the investigation of CEA greenhouses in Trinidad by first designing and constructing a prototype CEA greenhouse and testing its performance against a similarly constructed naturally ventilated greenhouse. This research will predict the feasibility of large-scale use of CEA greenhouses in Trinidad and Tobago and in the Caribbean.

2. Existing Methods for Modifying the Environment in CEA Greenhouses

De Gannes et al. (2014) identified the following problems with CEA greenhouses in the Caribbean: high temperatures, high relative humidity, high carbon dioxide concentration, low oxygen, reduced light especially below minimum threshold level during rainy/cloudy days.

Karlsson (2014) reviewed the various methods of controlling environment in greenhouses (see Figure 1). For instance, temperature is controlled by using natural ventilation, exhaust fans, evaporative cooling, mist cooling and shade curtains. Relative humidity is modified by using circulating fans, exhaust fans, natural ventilation and dehumidifiers. Supplemental lighting is provided using incandescent light bulbs, halogen incandescent bulbs, fluorescent bulbs, high intensity bulbs or light-emitting diodes (LED) lights.



Reduce Temperature	Natural Ventilation	Exhaust Fans	Evaporative Cooling	Mist Cooling	Shade Curtains
Reduce Humidity	Circulating HAF Fans	Exhaust Fans	Ventilation	Dehumidifiers	
Air Movement	Circulating HAF Fans	Ventilation	Exhaust Fans		
Supplemental Lighting	Incandescent	Halogen Incandescent	Fluorescent	High Intensity Discharge	Light Emitting Diodes

Figure 1. Methods of controlling greenhouse environment

In a CEA greenhouse, an integrated computer system is used to ensure that ventilation, humidity, light intensity, carbon dioxide levels and all other parameters operate in harmony with one another so as to provide the best growing conditions (Albright and Langhans, 1996). While simple on-off switches may be used, a computerised system offers remote monitoring and controls based on specific plant requirements (Karlsson, 2014; Goldammer, 2017). Sensors are placed in greenhouses to acquire data. For sensors to be effective, they must be kept at plant canopy height with limited direct influence from vents, fans or drafts (Karlsson, 2014).

In computerised systems, sensors send data through a data acquisition (DAQ) device for signal conditioning or through an analogue-to-digital converter (ADC) to computer software to analyse and process this data, to activate some type of control. Information from the computer software is used to activate the actuators using digital-to-analogue convertors. Thermostats or controllers are also utilised in CEA greenhouses. While thermostats control temperature, controllers continuously monitor the greenhouse environment (Karlsson, 2014). Cheap and non-complex on/off systems (Goldammer, 2017) allow sensors to be directly connected to environmental controllers that use relay controls to switch on and off of pumps and fans. This is one way of reducing the cost of CIA greenhouses and was adopted in this study.

3. Design and Construction of Prototype Greenhouses

Two prototype greenhouses were constructed and placed alongside each other (see Figure 2). Both greenhouses utilise the Quonset structure which has been altered to improve natural ventilation, by means of a butterfly vent. De Gannes et al. (2014) recommended the Quonset model of greenhouse with a split-roof as the best for the Caribbean region. Sahadeo et al. (2017) modelled and tested this model and verified this recommendation. Greenhouse A is a CEA greenhouse, while Greenhouse B is also a protected agriculture structure but with natural ventilation as the only means for controlling environment. The latter greenhouse was constructed so that both greenhouses could be tested side to side to see if there are advantages of the CEA greenhouse. Each greenhouse is 2 m length, 1.5 m width and 2 m depth.

The framework of the greenhouses was constructed with 12.5 mm and 25 mm-diameter polyvinyl chloride (PVC) pipes. PVC cement was used to stick all the pipes into their fittings. The greenhouse frame was covered with a 0.15 mm thick, ultra violet (UV) resistant, low density, clear polyethylene glazing material with a light transmittance of 80% to 90%. The main structure and glazing of protected greenhouses have been fully described by Sahadeo et al. (2017). Figure 3 shows the diagram of the CEA greenhouse (Greenhouse A).


(a) Greenhouse A: With controlled environment
(b) Greenhouse B: With no controlled environment

Figure 2. The two constructed prototype green houses

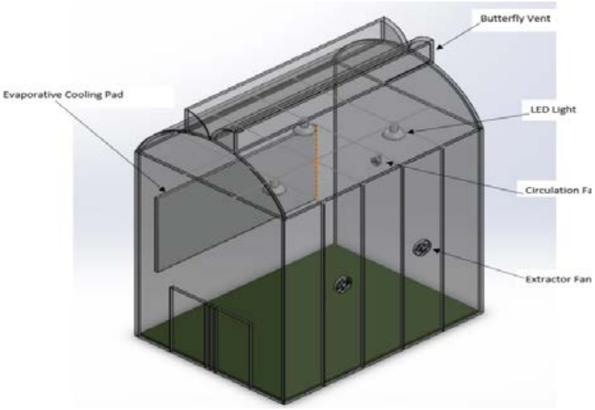


Figure 3. Controlled Environment Agriculture greenhouse (Greenhouse A)

Temperature control was achieved using two extractor fans (each 30.5 cm diameter) and a pad evaporative cooling system. The pad frame (1.6 m width, 0.8 m height and 0.762 m thickness) was constructed using pitch pine pieces. The pad material was shredded coconut fibres. Deoraj et al. (2015) found that coconut fibres are efficient for local use as pad material in evaporative coolers. For maximum efficiency and effectiveness, the greenhouse was designed to be air-tight, so that there was no disruption in or alternative path to airflow. Extractor fans drew the air from outside through the pad, since nature does not allow for a vacuum. The pad was continuously being wetted by a 0.01 hp pump (not shown in Figure 3) which supplies water to it from a tank.

As the air passed through the wet pad, it was cooled by evaporation. Evaporative cooling, however, works best in less humid conditions, since the cool, moist air being drawn through the pad adds humidity to the environment. The efficiency of evaporative coolers was tested in Trinidad by Deoraj et al. (2015) with some limited success. The CEA greenhouse therefore utilised in addition, natural ventilation so as to ensure that even without any of the automated systems being engaged, air was constantly exchanged between the external and internal environment, so that the crops got a fresh intake of air regularly.

As the hot air expands and rises, it escapes the greenhouse through the butterfly vent. When the internal temperature of the greenhouses exceeds maximum threshold of about 35^{o}C (monitored by a temperature controller), the evaporative cooling system will be activated, the exhaust fans and pump will switch on and the evaporative cooling process will start. When the temperature drops to the optimum level, the system will disengage. When the humidity inside the greenhouse exceeds 70% (monitored by a humidity controller), the two circulating fans (each 100 mm diameter), will switch on. When the humidity drops below 70%, the circulating fans will switch off. However, if the exhaust fans of the evaporative cooling system are on, the circulating fans will not switch on and vice versa. This is to avoid turbulence and vortices from developing due to the simultaneous circulation of air and the air being pulled through the greenhouse by the extractor fans.

Supplementary lighting was achieved using three light emitting diode (LED) fixtures. LED grow lights (Figure 3) have several advantages over traditional light sources: They are energy efficient, cheap to maintain and are long-lasting (Karlsson, 2014). The LED lights encourage photosynthesis and crop growth (Tian et al., 2014; Suraj, 2017).

4. Testing of the Constructed Prototype Greenhouses

Two tests were carried out. The first test examined the efficacy of the coconut fibre as an evaporative pad on two operating parameters of evaporative cooler (saturation efficiency of the evaporative pad and the temperature difference between the ambient conditions and the inside of the CEA greenhouse). The procedure used by Deoraj et al. (2015) was used in this study. A tank was filled with pipe-borne water (T_{avg} = 28.6^{o}C) and the pump was switched on. The airflow rate of the extraction fans was measured with an anemometer. Wet and dry bulb thermometers were used to measure the wet and dry bulb air temperatures entering the evaporative pad and another dry bulb thermometer was used to measure the temperature of the air entering the greenhouse. Temperatures were measured every 15 mins for 3 hours. The test was performed in the morning (9.00 a.m. to 12 noon) and it was repeated in the evening from 1 p.m. to 4 p.m. The saturation effectiveness of the evaporative cooling pad was calculated using the Equation 1 (ASHRAE, 2007).

$$\varepsilon = \frac{t_1 - t_2}{t_1 - t'} \text{ x } 100 \qquad (1)$$

Where ε is saturation efficiency (%), t_1 is dry bulb temperature of entering air (K), t_2 is dry bulb temperature of leaving air (K) and t' is the wet bulb temperature of entering air (K).

The second test involved the planting of some vegetable crops in both greenhouses to test the efficiency of the CEA greenhouse. Two plant troughs, each 120 cm length and 60 cm width were filled with peat moss mix to a depth of 20 cm, and placed in the two greenhouses (see Figure 2). The troughs had openings at the bottom which allowed for drainage. Seedlings of the same maturity (two weeks old) collected from a nursery were transplanted to the two troughs. The crops in each trough included 3 plants of 535 variety roma tomatoes (Solanum lycopersicum 'Roma'); 3 plants of bronze lettuce (Lactuca sativa Mignonette Bronze**)**; and 3 plants of pak choi (Brassica rapa spp. Chinensis).

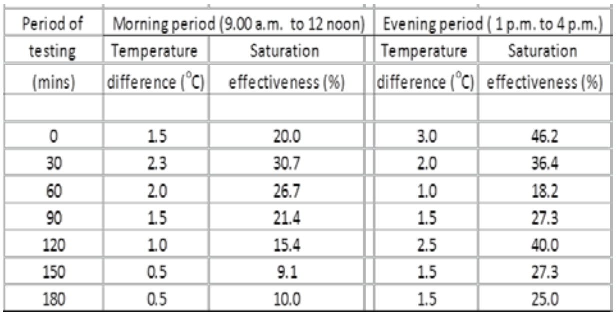
The troughs were manually watered every day at 9.00 a.m. at the rate of 9 Litres day^{-1} for the three weeks of testing. A fungicide (Carbendazim, 50SC) was sprayed onto the leaves of each plant weekly. Plant heights, and stem diameters were measured three times a week with a ruler and Vernier caliper respectively. Leaf areas of each plant were measured using a grid paper. The ambient temperature and humidity as well as those for the greenhouse with natural ventilation were measured with a digital thermo-hygrometer, while those for the CEA greenhouse were recorded by temperature and humidity controllers. Readings of temperature and humidity were taken from 9.00 a.m. to 12 noon, as well as from 1.00 p.m. to 4.00 p.m. every two days.

5. Results and Discussion

5.1 Saturation Effectiveness and Temperature Difference

Table 1 shows the saturation effectiveness of the evaporative cooling pad and the temperature difference between the ambient air and inside of CEA greenhouse (Greenhouse A). The average saturation effectiveness attained for the coconut fibre pad was 25.3% (morning: 19% and 31.5% in the evening). The saturation effectiveness corresponds to temperature difference

Table 1. The temperature difference between the ambient air and inside of CEA greenhouse



Period of testing (mins)	Morning period (9.00 a.m. to 12 noon)		Evening period (1 p.m. to 4 p.m.)	
	Temperature difference (°C)	Saturation effectiveness (%)	Temperature difference (°C)	Saturation effectiveness (%)
0	1.5	20.0	3.0	46.2
30	2.3	30.7	2.0	36.4
60	2.0	26.7	1.0	18.2
90	1.5	21.4	1.5	27.3
120	1.0	15.4	2.5	40.0
150	0.5	9.1	1.5	27.3
180	0.5	10.0	1.5	25.0

Saturation effectiveness and temperature difference, as expected, were higher in the evening than in the morning and this agrees with results by Dagtekin et al. (2009) as the weather conditions throughout the day affected the system.

These values were much lower than the corresponding average values of 53.5% and 3.6 °C found by Deoraj et al. (2015) for coconut fibres similar to the ones used in this test. They operated their fans at 4 m/s, 6 m/s and 8 m/s compared to average of 2.4 m/s speed of the extraction fan in the present tests. Several other factors which affect pad performance including surface area of the pad, pad thickness, size of perforation of the pads, relative humidity of air passing the pad, volume of water used and number of layers may also have contributed to the lower values obtained (Sreeram, 2014).

5.2 Temperature and Humidity in the Ambient Air and in Greenhouses A and B

Figures 4 and 5 show the average daily temperature and humidity of the ambient air as well as those in Greenhouses A and B during the crop growth test period, respectively.

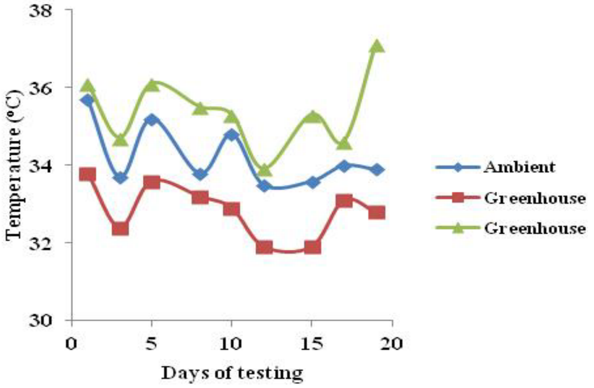


Figure 4. Temperature of the ambient air and inside the two greenhouses

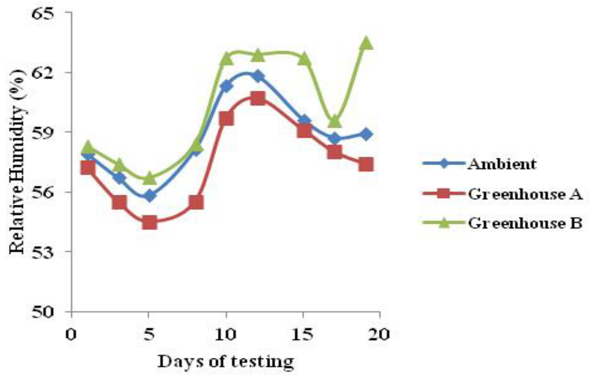


Figure 5. Relative humidity of the ambient air and inside the two greenhouses

Results show that the temperature and relative humidity inside the CEA greenhouse (Greenhouse A) were lower than those for the ambient air.

This is not surprising since the temperature and relative humidity of the CEA greenhouse were controlled via evaporative cooling and air circulation, respectively. The reverse was obtained for Greenhouse B where the lack of control meant that the two parameters were higher than the values for the ambient air. It was shown in Section 5.1 that the evaporative system was able to effectively reduce the temperature from ambient conditions by 1.6°C. Greenhouse B on the other hand had no accommodation for control of air movement other than natural ventilation, making the humidity higher than that in the CEA greenhouse.

5.3 Plant Growth Parameters in the Two Greenhouses

The plant parameters used to compare the performance of the two greenhouses were plant height, plant diameter and leaf area. Obtaining the three parameters required non-destructive tests. Table 2 shows the values of the plant height and plant diameters of the three vegetable crops. Average growth rates for the height and diameter were calculated by subtracting the initial value of the parameter from the final value and dividing by the test period (19 days). The heights and diameters of all the three crops were much higher in the Greenhouse A (CEA greenhouse) than in Greenhouse B with natural ventilation.

On the average, the average growth rates in the Greenhouse A, in terms of height, were at least 1.77, 2.67 and 3.88 of the values in the Greenhouse B for tomatoes, lettuce and pak choi, respectively. For the crops, the respective values for plant diameter were 1.12, 2.4 and 55. This suggests that the CEA greenhouse was most effective for the pak choi and least for tomatoes. Thus, it is evident that a combination of all the control variables (temperature, humidity, light intensity and air movement) was responsible for the improvement in plant growth in the CEA greenhouse.

Wheeler et al. (1991) were the first to propose that plant developmental response to blue light (400 – 500 nm) was dependent on absolute blue light for stem elongation in soybean. Blue wave lights affect phototropism, the opening of stomata (which regulates a plant's retention of water) and chlorophyll production (Reece and Campbell, 2011). Crops in CEA greenhouse were grown under LED blue light. Plant stem diameter changes due to both cambial growth (microstructural layer responsible for secondary growth of stems and roots) and water content (Sevanto, 2003). With higher temperature, the plant transpires at a faster rate, causes exhaustion and lack of water retention in the stem of the plant.

Figure 6 shows the growth of the leaves in the three crops during the testing period. The results followed the same trend as for plant height and stem diameter discussed above, with the CEA greenhouse having much larger areas for the three crops than Greenhouse B (about two and half times on the average). The best results for the CEA greenhouse were obtained for pak choi followed by lettuce and then tomatoes. The values widened as time of testing increased showing that the differences in plant development between the two greenhouses are expected to increase as the growth period extends.

Shin et al. (2001) found that leaf area, stem length and stem diameter generally increased with decreasing temperature. Wang et al. (2014) demonstrated that LED blue light optimised photosynthetic performance by improving the photosynthetic rate, increasing leaf area and prolonging active photosynthesis duration under low irradiance. Chlorophyll absorbs light within the range of 400-500 nm most effectively (red and blue light).

Table 2. Growth parameters for the three crops during the test period

Days after planting	Tomatoes		Lettuce		Pak choi	
	Height	Stem diameter	Height	Stem diameter	Height	Stem diameter
	(cm)	(x 10^{-1} cm)	(cm)	(x 10^{-1} cm)	(cm)	(x 10^{-1} cm)
1	11.0*/11.0	0.154/0.155	7.6/7.0	0.297/0.294	5.7/5.7	0.197/0.196
3	12.4/12.3	0.161/0.159	8.9/7.1	0.313/0.310	8.6/6.0	0.207/0.199
5	14.9/14.4	0.171/0.165	9.9/7.7	0.321/0.314	9.9/6.9	0.234/0.214
8	20.5/16.9	0.195/0.179	11.2/8.1	0.331/0.318	11.2/7.6	0.303/0.215
10	23.5/18.5	0.219/0.193	11.9/8.6	0.335/0.320	13.0/8.3	0.326/0.223
12	26.6/19.6	0.225/0.213	13.0/9.1	0.346/0.326	14.6/8.9	0.367/0.243
15	29.6/21.6	0.247/0.245	14.0/9.5	0.368/0.338	15.9/10.2	0.387/0.257
17	30.0/21.7	0.257/0.246	14.6/9.7	0.383/0.339	16.1/10.4	0.416/0.264
19	30.2/21.9	0.259/0.248	15.2/9.9	0.405/0.340	16.4/10.5	0.435/0.278
Average growth rate (cm or mm day^{-1})	1.01/0.57	0.0055/0.0049	0.40/0.15	0.0057/0.0024	0.97/0.25	0.238/0.0043

*- Values of the growth parameters are average for the three plants in the Greenhouse A/Greenhouse B.

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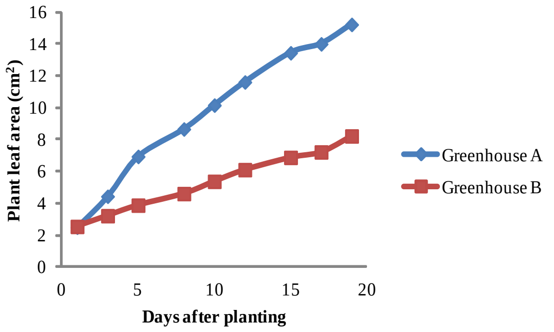
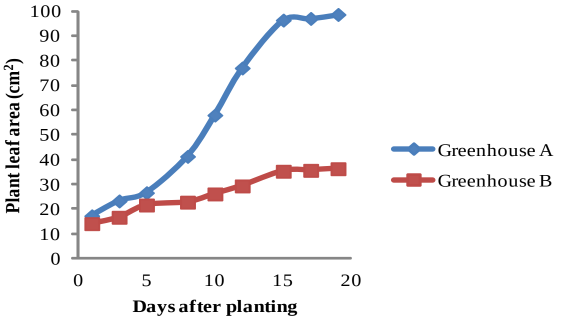
(a) **Tomatoes**



(b) **Lettuce**



(c) **Pak Choi**

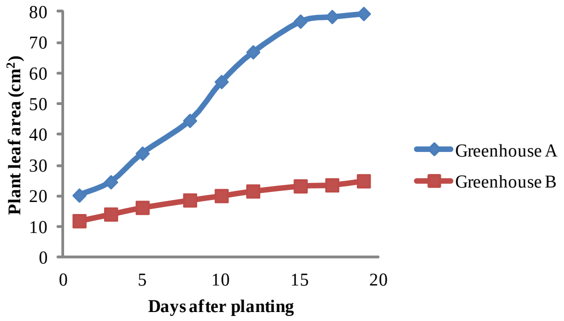


Figure 6. Values of mean leaf area for the three types of crops in the two greenhouse during the testing period

6. Conclusion

A CEA greenhouse was designed, built and tested by examining the effects of different control parameters on system performance and plant growth. The saturation effectiveness of the pad and temperature difference between the ambient and the inside of the CEA greenhouse were found to be 25.3% and 1.6°C respectively. The impact of controlling temperature and humidity on the CEA greenhouse was assessed, by comparing the results to those of the non-controlled environment and ambient conditions. The results indicated that the controlled environment provided effective cooling and humidity reduction, whereas the non-controlled environment elevated ambient temperature and humidity conditions. Plant growth parameters (height, stem diameter and leaf surface area) within the CEA greenhouse were much greater than those for the naturally ventilated greenhouse.

The combination of using blue LED light, evaporative cooling, and air circulation fans coupled with natural ventilation gave a significant improvement in plant growth rates in the CEA greenhouse. The total cost for two greenhouses was about US$ 600. Further work will evaluate the efficiency and cost of fully functional CEA greenhouses so as to further validate these findings. Instead of the simple on/off switches method utilised to control the CEA greenhouse environment, an integrated computer control system will be investigated in future research.

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