Chapter

The Canadian Integrated Northern Greenhouse: A Hybrid Solution for Food Security

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Abstract

Food security has become a prominent issue in northern Canada. Many constraints, including environmental, cultural and economic barriers to cause food insecurity in northern Canada where local food production is one proposed solution to the northern food crisis. Initiated at McGill University by the Biomass Production Laboratory, the Canadian Integrative Northern Greenhouse (CING) unit provides a completely integrative design solution that could allow northern Canadian communities to grow their own fresh and nutritious food year-round. The CING unit is a hybrid between a northern greenhouse and a growth chamber housed in a shipping container, designed to be adaptive by functioning as a typical solar greenhouse when solar light provides considerable heat and light, and as a closed growth chamber during the night and when colder, darker winter conditions prevail. The CING was designed and prototyped by McGill students since 2013. Lettuce was grown during the four-season test of the CING, the greatest yield obtained was in March 2019, where the plants grown achieved 72% of the dry mass of the plants grown in the research greenhouse. The CING relied on supplemental heating to successfully grow plants but demonstrated the potential for northern and remote applications.

Keywords: shipping container farming, controlled environment agriculture, northern agriculture, northern greenhouse, organic fertilizer

1. Introduction

The CING is designed as a hybrid between a closed growth chamber and a greenhouse to optimize energy requirements related to the production of fresh produce throughout the year. The unit can open to allow sunlight to enter, utilizing the unit's greenhouse function, or be completely covered by an insulated thermal curtain, employing the unit's growth chamber function. Specific exterior and interior conditions dictate when the use of each mode is most efficient to promote the best interior conditions. To determine and predict these conditions, climatic and environmental data were recorded outside and inside the CING prototype situated at McGill University's Macdonald Campus in Sainte-Anne-de-Bellevue, QC, since summer 2015.

1.1 Container farming

Container farming (CF) is an indoor agricultural practice falling under the Controlled Environment Agriculture (CEA) category [1]. Plants are grown hydroponically in a shipping container with electrical lighting and most of the environmental parameters are controlled by the grower. Converting a shipping container into an indoor farm has many advantages. First, a shipping container is an inexpensive infrastructure. Buying a refurbished shipping container and modifying its structure by cutting through the walls is still considered cheaper than buying a new building. Second, transportation, if the structural components of a shipping container are intact (i.e. the four corner beams), the CF has a strong foundation that can be moved as a typical shipping container. In this way, it acts as a mobile agricultural unit. Third, a converted shipping container's internal environment is independent of environmental parameters. In an insulated environment comprising electrical lighting, soil-less cultures, and heating ventilating and air conditioning (HVAC) technologies, it is possible to grow crops in any climate. Finally, a converted shipping container offers a high yield per square meter. Using vertical farming in which five levels of shallow water hydroponic cultures of lettuce are stacked, it is possible to grow 20 times more produce per square meter in a CF than field agriculture with corresponding yields of 1000 plants. m^{-2} [2].

CF is still a relatively new agricultural practice, and indoor farmers do not necessarily agree that this new agricultural practice is economically viable, still being considered an overhyped technology, with only 50% of container farms being profitable in the U.S. [3]. Yet CF has many different styles, with companies such as Freight Farms, Growtainers, and Cubic Farms offering similar options to grow crops in urban or remote areas [4] (**Figure 1**). According to case studies from companies like Bright Agrotech and independent reports from universities such as the University of Bonn in Germany and the Massachusetts Institute of Technology, vertical farming and CF can be economically profitable and viable depending on different economic parameters, such as market, labor and cheap energy availability [5].

The concept of a modified shipping container for controlled environment agriculture is not new (**Figure 2**). Strategies using modified shipping containers with natural lighting has been made for conditions comparable to those found in New York City and Los Angeles by the University of Arizona. From these simulations, it was determined that shipping containers with transparent walls have a much lower energy consumption than opaque and well-insulated walls (**Table 1**) [6].

Figure 1.
Outside of the CING, December 2017.

Figure 2.
A module for the Minimally Structured & Modular Vertical Farm, designed by Dr. Cuello from the University of Arizona (Liu, 2014).

Annual Energy Estimation (kWh/m^2)	Los Angeles		New York City	
	Transparent wall	Opaque wall	Transparent wall	Opaque wall
Tomato	240.06	381.30	557.65	325.34
Lettuce	418.38	1950.99	773.84	1640.85

Table 1.
Summary of annual energy consumption in kWh/m2 [6].

From these energy values, except for growing tomatoes in a transparent wall shipping container in New York City where the well-insulated opaque wall helped reduce heat loss in a colder month, using transparent walls in a shipping container would reduce the energy needs to grow certain food crops in CF, even for Lettuce during cold months [6]. Following these findings, the CING was not modeled for its energy use, rather, design and experimental approach was chosen to test the use of natural lighting in CF in a cold climate.

2. Materials and methods

2.1 Design of the CING

The CING was first designed in 2013 by Bioresource engineering students at McGill University (**Figures 3** and **4**). A shipping container was purchased in 2015.

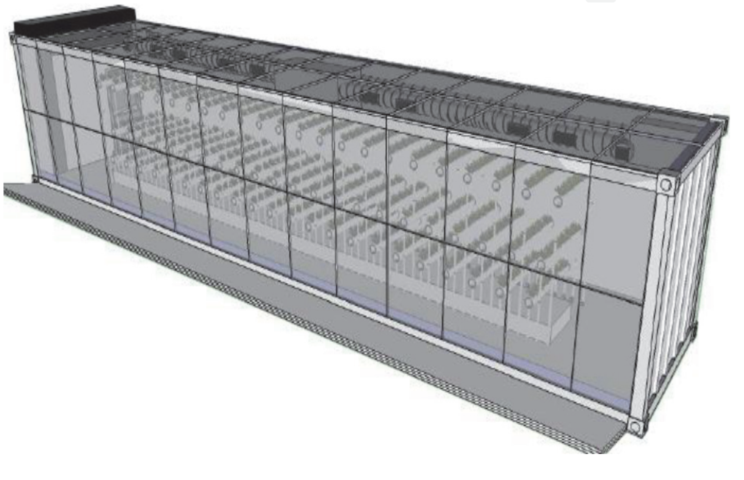

Figure 3.
Original design of the CING.

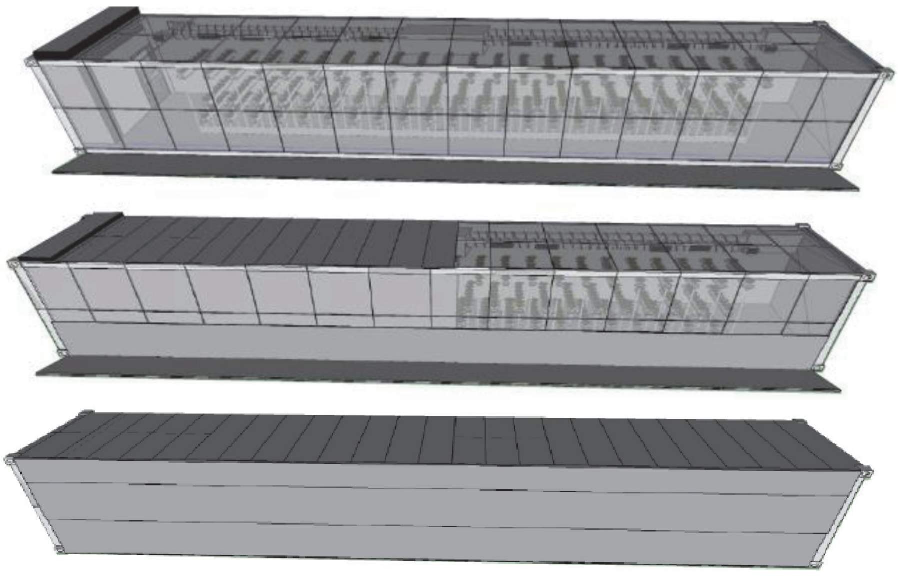

Figure 4.
Representation of the opening and closing of the outside panels.

One of its walls and the roof were replaced by polycarbonate sheets to allow the shipping container to use natural light for growing purposes.

Only half of the 40-foot shipping container was used for growing space. The CING design includes insulating panels that can open and close (added in 2015) to benefit from natural light when available (**Figures 5** and **6**). Their opening and closing were operated by 2000-lb winches controlled by an Arduino Mega (Adafruit Industries, US).

A growth tower was designed to allow inter-canopy lighting of the crops, optimizing the use of the supplemental electrical light. The growth tower was originally designed for drip irrigation (**Figure 7**).

In 2017, the tower was converted to a nutrient film technique (NFT). A comparative tower was built using a similar inter-canopy pattern for testing the CING's performance which was placed in a research greenhouse at McGill University's Macdonald Campus (**Figure 8**).

Figure 5.
Opening (left) and closing (right) of the CING insulating panels.

Figure 6.
Opening (right) and closing (left) of the CING rooftop panels.

Figure 7.
Original design of the CING growth tower (left), side-view (top right) and solution tank (bottom right), pictures by Thanh Jutras, 2016.

2.2 Energy usage

One of the CING operational challenge was using minimal energy consumption. It was determined that the CING must be operational on a 30-Amp, 110 V-circuit year-round, for maximum daily energy usage of 79.2 kWh (**Table 2**) (Eq. 1).

$$\text{Energy (kWh)} = \text{Current(A)} * \text{Voltage (V)} * \text{time (h)}/1000 \qquad (1)$$

For this reason, supplemental lighting and heating are limited, but the use of natural light as a light and heat source for the growing environment was the main parameter studied to evaluate the CING's potential as an energy-efficient indoor growing system adapted for a northern climate.

Under cold weather conditions, the exhaust fans were not used while in warm weather the heaters were not used resulting in maximum daily energy uses of 29.4

Figure 8.
Comparative growth tower in the research greenhouse, Summer 2018.

Equipment	AC Current (amps)	Voltage (V)
Irrigation pump (4 pumps)	3.2	110
Heaters	13.8	110
LED lights	3.3	110
Automation control system	1*	110
Motor for thermal curtains	1*	110
Exhaust fans	2.12	110
Total	24.42	110

**The estimated current was required for automation system and thermal curtains function.*

Table 2.
Electrical current and voltage consumption of the CING environment control system components [7].

kWh.m^{-2} and 14.0 kWh.m^{-2} respectively. These values were obtained using only a small, representative growing area of 2 m^2. The growing area of half of 40-foot shipping is 14.4 m^2. More lighting, pumping capacity and air exchange would be needed if the full growing area was used.

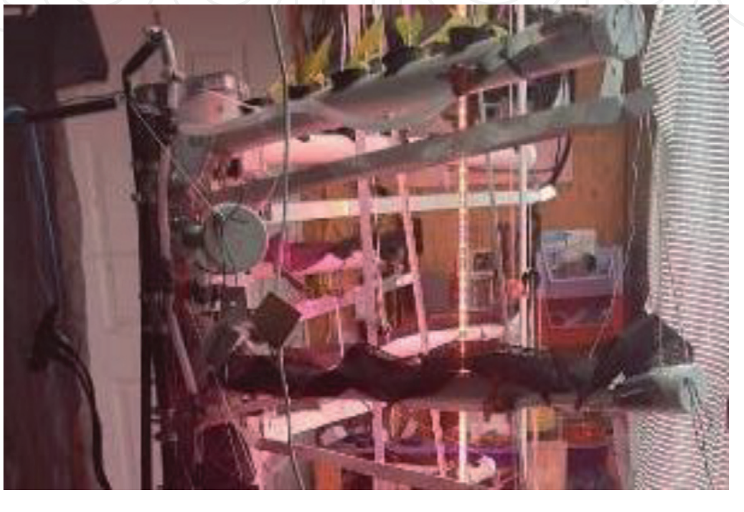

Figure 9.
Inside the CING, on the right is the closed thermal curtain, Winter 2019.

2.3 Thermal curtain parameters

A thermal curtain (TEMPA 7567 D FB, Svensson, North Carolina, U.S.), allowed a transition from greenhouse mode to growth chamber mode (**Figure 9**). The thermal curtain was functional and set to open when solar irradiation was above 12 $W.m^{-2}$ and close when irradiation went lower than the set value. This value was recommended in a previous report on the recommended operating conditions of the CING [7].

2.4 Growth experiments

The CING ran for four consecutive seasons: Spring 2018 (May 7th to June 6th), Summer 2018 (June 8th to July 2nd), Fall 2018 (December 1st to December 22nd) and Winter 2019 (March 1st to March 23rd).

2.5 Biological nutrient solution testing

Since both growing systems had two independent pumps for the right and left sides, two nutrient solutions were tested in each system. The first was a one-quarter strength Hoagland solution [8] and the second comprised a biological nutrient solution based on vermicompost leachate. This solution was continuously prepared during the experiment using 10 L vermicompost, fed a constant diet of eggshells, banana peels, coffee grounds and cardboard. By flooding the vermicompost weekly with 1 L water, the leachate was collected and diluted to match the electrical conductivity (EC) of the Hoagland nutrient solution.

2.6 Hydroponic systems parameters

2.6.1 Design

The hydroponic growth systems were built as growing towers (**Figures 10** and **11**). The growing systems were 6-feet high (183 cm), each containing 16 42-inch (107 cm) long tubes, where six lettuce plants can grow using NFT, resulting in 96

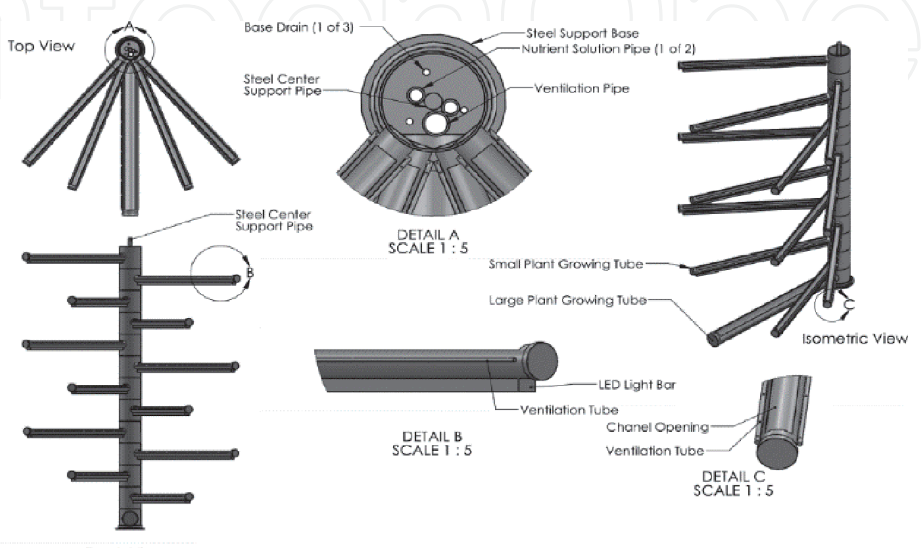

Figure 10.
The hydroponic growing tower system for the research greenhouse (left) and growing system in the CING (right).

Figure 11.
Growing system prototype design described previously [6].

lettuce plants total per system. Tube diameters were 2 inches (5 cm) in diameter and lettuce heads were held in 2-inch (5 cm) net pots (**Figure 11**).

2.6.2 Flow in hydroponic systems

Each side of the growing systems has an independent pump. The nutrient solution is pumped by a magnetic drive submersible water pump (EcoPlus, Eco 396, US), delivering a flow of 1500 L.h^{-1} (396 GPH), at a height of 2 m. A valve was used to control the flow in each tube, and a 1 L.min^{-1} flow ensures a 3-mm level of nutrient solution in the 5 cm tubes [9]. Four NFT tubes per experiment were tested, to ensure 0.6–1 L.min^{-1} per tube.

2.6.3 Electrical conductivity (EC)

EC was monitored with a handheld EC-meter (HM Digital Meters COM-80 Electrical Conductivity and Total Dissolved Solids Hydro Tester, Seoul, Korea). The EC was kept between 115–125 mS/m ($\pm$ 2.5 mS/m) above the greenhouse's irrigation water EC. The EC was adjusted by adding greenhouse irrigation water or concentrated nutrient solution [10]. pH

The pH of both nutrient solutions was maintained between 5.50 to 7.00 ($\pm$0.01). It was monitored with a handheld pH-meter (Dr. Meter PH100, China). Phosphoric acid (19.7% w/w) was used to lower pH to the desired value.

2.6.4 Light

Electrical light in the CING unit was provided by an LED installation. This comprised 10 light strips installed underneath the NFT tubes and six vertically hung light strips. When the thermal curtain was open, natural light was made available. In the Fall trial, the thermal curtain was only open when solar radiation was over 12 W/m^2 [7]. The outside light was measured with a Solar Radiation Smart Sensor (ONSET, Massachusetts, US), with a range of 0 to 1280 W/m^2 $\pm$ 10 W/m^2. Light intensity to activate the thermal curtain was measured with a TSL2561 luminosity sensor, measuring Lux.

The natural lighting in the research greenhouse was supplemented with a high-pressure sodium (HPS) lamp lighting system. To ensure good growth, combined lighting is approximately 17 mol/m^2/day. The targeted instantaneous light intensity, measured with the LI-250A Quantum Radiometer Photometer, was estimated at

197 ± 1 μmol/m^2/sec. However, we expected that lighting would sometimes be lower than this targeted value, and the lowest light intensity value was estimated at 50 ± 1 μmol.m^{-2}.sec^{-1}. Lightmapping of the system was made to determine the amount of light achievable in both systems (Appendix A Tables A-5 to A-13) [10].

2.6.5 Temperature and relative humidity

The internal CING temperature set point was 24 °C during the day and 19 °C during the night time. This temperature was maintained using an electric auxiliary heater connected to an electrical thermostat (LUX Win100, Philadelphia, Pennsylvania). For the fall and winter trials. Auxiliary electrical heating was necessary and almost constant.

The internal temperature in the CING was monitored with a 12-Bit Temperature/Relative Humidity sensor (± 0.2 °C from 0° to 50 °C; ± 2.5% from 10% to 90%) compatible with the Hobo data logger (ONSET, Massachusetts, US). Humidity levels were not controlled.

The heating, ventilation and air-conditioning (HVAC) system were not functional for the test trials. However, exhaust fans were set on a thermostat, pulling fresh air into the CING, reducing temperature and relative humidity. A 9-inch 1100 CFM and a 16-inch 1435 CFM exhaust fan (Hessaire, Phoenix, Arizona, US) were mounted on the side wall, set on an electrical thermostat LUX Win100, Philadelphia, Pennsylvania) to cool the CING at 27 °C.

2.6.6 Crops

Romaine lettuce *(Lactuca sativa)* was cultivated for the first three trials (Spring 2018, Summer 2018 and Fall 2018), and Boston lettuce (*L. sativa)* was grown in Winter 2019 due to lack of available seeds.

2.7 Parameters

2.7.1 Light mapping

Lightmapping of the systems was made using a handheld Li-Cor Li-250A light sensor (LI-COR Biosciences, NE, US). To get the daily light integral (DLI) (mol. m^{-2}.d^{-1}), the photosynthetically active radiation (PAR) obtained at the brightest moment in the day was deducted from the PAR provided by the supplemental lights provided (PAR measurement after sundown), in the greenhouse and in the CING. PAR from the supplemental HPS lights in the greenhouse was 56.69 μmoles.m^{-2}.s^{-1} and PAR from the supplemental LED lights in the CING was 37.58 μmoles.m^{-2}.s^{-1}. Assuming that a quadratic function represents PAR versus the time of day for the

	Vermicompost Nutrient Solution				**Hoagland Nutrient Solution**			
Trial	**pH**	**EC (ms/m)**	**Temp. (°C)**	**Vol.(L)**	**pH**	**EC (ms/m)**	**Temp. (°C)**	**Vol. (L)**
1	9.1	129.9	31.7	13.8	7.9	160.2	30.3	12.2
2	6.4	140.8	26.4	15.0	6.5	146.8	26.4	15.5
3	6.9	109.5	22.6	12.9	6.6	118.4	21.9	12.4
4	5.1	146.7	24.0	14.5	4.9	84.5	23.1	11.3

Table 3.
Averages of monitored nutrient solution parameters for all trials (trial 1, 2, 3 and 4 respectively correspond to spring 2018, summer 2018, fall 2018 and winter 2019) in the research greenhouse.

	Vermicompost Nutrient Solution				Hoagland Nutrient Solution			
Trial	pH	EC (ms/m)	Temp. (°C)	Vol. (L)	pH	EC (ms/m)	Temp. (°C)	Vol. (L)
1	8.9	117.2	20.0	14.9	8.0	119.5	19.5	15.1
2	6.4	128.5	26.3	22.0	6.3	132.3	26.0	23.5
3	6.9	68.2	10.7	10.3	6.6	128.2	10.2	18.7
4	7.4	123.2	19.6	16.3	7.3	114.5	19.3	14.1

Table 4.
Averages of monitored nutrient solution parameters for all trials (trial 1, 2, 3 and 4 respectively correspond to spring 2018, summer 2018, fall 2018 and winter 2019) in the CING.

length of the specified day, with the measured PAR value at its highest value during daytime, it was possible to evaluate the maximum daily light integral from the Sunlight for a specific trial. By adding the DLI from the sun with the DLI of the supplemental light, a total maximum DLI was obtained.

For the Summer trial, PAR was measured on June 19th, 2018 under clear skies, assuming a 16-h day and 8-h night during the entirety of this trial. DLI in the greenhouse was evaluated at 29.4 mol/m^2/d and DLI in the CING was evaluated at 20.9 mol.m^{-2}.d^{-1}. For the Fall trial, PAR was measured on December 20th, 2018 under clear skies, assuming a day length of 8 h 50 min during this trial. DLI in the Fall in the greenhouse was evaluated at 5.1 mol.m^{-2}.d^{-1} and 7.61 mol.m^{-2}.d^{-1} in the CING. For the Winter trial, PAR was measured on March 19th, 2019 under clear skies, with an average daytime of 12 h, assuming the same PAR from supplemental lighting in the greenhouse and the CING from previous experiments. DLI in Winter in the greenhouse was evaluated at 18.0 mol.m^{-2}.d^{-1} and in the CING was evaluated at 9.3 mol.m^{-2}.d^{-1}. PAR mapping of the systems is available in Appendix A.

2.7.2 Monitoring of systems

The EC, pH, temperature and volume of the nutrient solutions for both systems were measured manually. Full monitoring data is available in the appendices and mean values for each trial are available in **Tables 3** and **4**.

2.8 Data analysis

Independent samples t-tests were performed using Excel to assess the statistical difference of the yields of fresh and dry masses of lettuce obtained in between growing environment for each trial.

3. Results

Season test Run	Spring				Summer			
Growth environment	GH		CING		GH		CING	
Treatment	V	H	V	H	V	H	V	H
Average fresh mass of lettuce (g)	0.82	33.63	0.64	4.60	4.81	53.25	1.86	7.41
S.E.	0.11	5.05	0.14	1.33	0.16	4.75	0.27	0.70
Season test Run	Fall				Winter			

Season test Run	Spring				Summer			
Growth environment	**GH**		**CING**		**GH**		**CING**	
Growth environment	GH		CING		GH		CING	
Treatment	V	H	V	H	V	H	V	H
Average fresh mass of lettuce (g)	2.51	17.54	0.99	0.97	4.38	23.40	2.07	16.79
S.E.	0.17	2.15	0.06	0.08	0.34	2.15	0.21	2.70

Table 5.
Average fresh mass with standard error (S.E.) for all treatments, greenhouse (GH) and CING, with Vermicompost (V) and Hoagland (H) nutrient solutions at harvest.

4. Discussion

4.1 Summary of results

Plants grown in the research greenhouse with the Hoagland nutrient solution had the highest fresh and dry mass for all tests (**Figure 12**). Of all the CING trials, the fresh and dry mass of lettuce grown in the CING with the Hoagland nutrient solution during the Winter trial was the highest (**Figure 13**). The Vermicompost nutrient solution had lower fresh and dry mass compared to the Hoagland in a common growing environment.

4.2 Environmental and growing parameters differences

Because of the climate difference between trials, the growth environment differed greatly in the CING. The lighting cycle for the Spring trial was 12 h day: 12 h night, the thermal curtain was active and roof panels were closed. In addition, pH was not controlled for this trial. The lighting cycle for the Summer trial was 12 h day: 12 h night, the thermal curtain was active and only one roof panel was open (**Figure 14**). The lighting cycle for the Fall trial was 16 h day: 8 h night, the thermal curtain was active and only one roof panel was open. The lighting cycle for the Winter trial was 24 h day 0 h night, the thermal curtain was not active and only one roof panel was open.

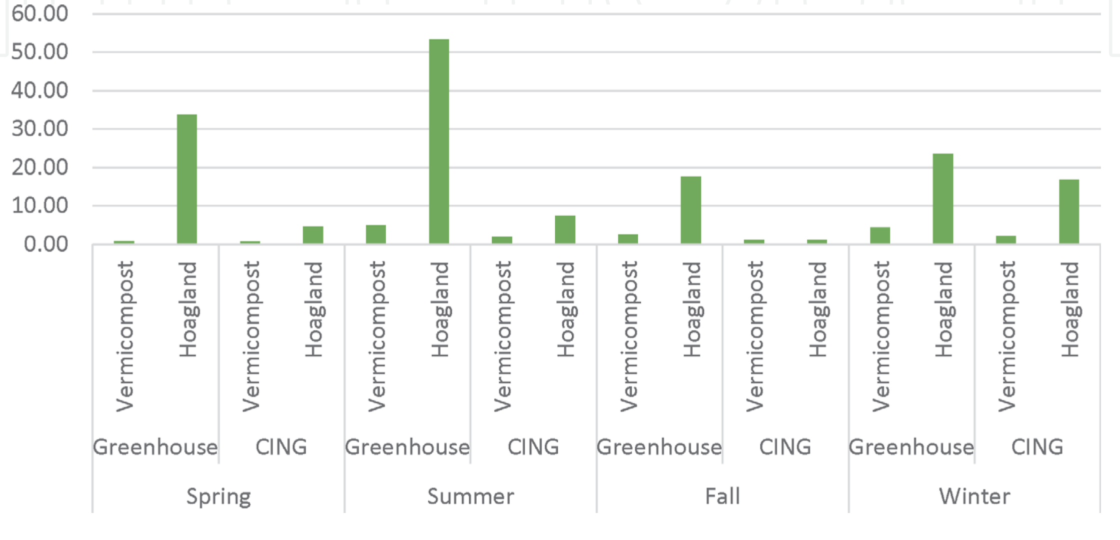

Figure 12.
Average fresh mass (g) of lettuce for all treatments at harvest.

Figure 13.
Lettuce grown in the CING before harvest, Winter 2019.

Figure 14.
Inside the CING, on top left is an opened roof panel, Summer 2018.

During the Spring trial, the pH in the vermicompost nutrient solution was over 8.5, pH was not controlled during the Spring trial and this may have limited nutrient availability and uptake.

During the Spring, Summer and Fall trials, plants in the CING grew very little when compared to plants grown in the greenhouse. During the Summer trial, the average temperature was slightly higher (25.4 °C) than the suggested temperature for lettuce growth (25 °C), and in the Fall the average temperature was 11 °C, which is lower than the recommended minimum (15 °C) for lettuce growth. Relative humidity for all trials ranged between of 50 to 70%, which is recommended for lettuce cultivation [10]. The Hoagland nutrient solution for the Winter trial was added at the beginning of the trial but not during; this explains the lower EC observed in the greenhouse for the Winter trial.

4.3 Cold weather trials

The Fall and Winter trials were the first cold climate trials undertaken in the CING unit. The comparison of the average conditions in the CING during both trial is available in the next table (**Table 6**).

For the Fall trial, the thermal curtain was set to open and close according to outdoor solar radiation. For the Winter trial, the thermal curtain remained closed, to help reduce thermal heat losses.

The curtain has an 80% shading level in diffused light PAR. The 20% of diffused light combined with the light from one opened roof panel, the constant supplemental lighting and the longer days allowed for greater DLI in the Winter Trial than the Fall trial. The average inside temperature in Fall was below the 15 °C recommended temperature for lettuce production [10]. This environmental difference explains the major difference in crop yield from the two cold conditions tests.

4.3.1 Thermal curtain

The thermal curtain usage changed the internal conditions of the CING. By comparing a set of days during both trials with similar outdoor temperature changes and environmental conditions, it is possible to better assess the impact of the thermal curtain. From December 10th to 12th 2018, the average outdoor and indoor temperatures were respectively, −7.6 °C and 12.3 °C. From March 4th to 6th 2019, the average outdoor and indoor temperatures were respectively, −8.2 °C and 7.5 °C.

Considering the thermal properties of the polycarbonate sheet, the thermal curtain and the insulating layer of air kept in between the thermal curtain and the polycarbonate sheet, with a temperature gradient of 15 °C from the inside and the outside of the CING the thermal heat loss from the window would be 17 Watts with the curtain closed, and 282 Watts with the curtain open. See the full heat transfer rate calculation in Appendix A.

Using the thermal curtain, the solar heat gain (SHG) to the CING was reduced, proportionally to the sunlight blocked, 80% [11]. This difference in SHG can be linked to the more stable temperature during the day, noticeable in **Figure 15** during the Fall trial cold days testing. However, during the Winter trial, with the thermal curtain constantly closed, the inside temperature was more dependent on the outside temperature as observed in **Figure 16** for a 3 days comparison with similar average temperatures.

This trend can be observed when comparing the relationship between the indoor and outdoor temperatures, during the 3 days comparison in **Figures 17** and **18** and the whole experiment data in **Figures 19** and **20**. Whereas the R^2 = 0.0656 for the

Trial	Average Outside Temperature (°C)	Average Inside Temperature (°C)	Approximate DLI ($mol.m^{-2}.d^{-1}$)	Average Fresh Mass (g)
Fall 2018	−3.9	11.0	7.6	0.97
Winter 2019	−2.4	14.8	9.3	16.79

Table 6.
*Summary of **Table 3**, **Table 4** and **Table 5** for cold condition trials of the CING.*

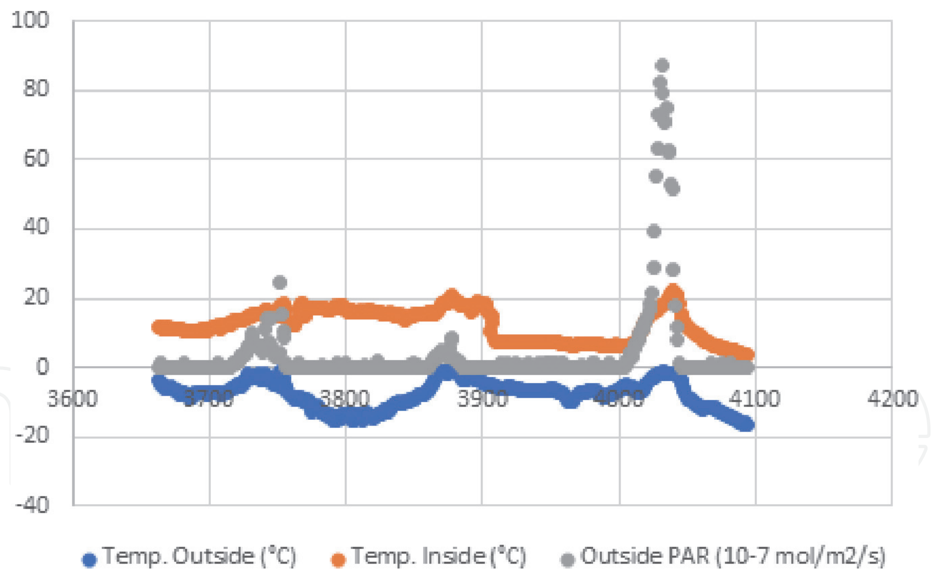

Figure 15.
Outside temperature, inside temperature and outside PAR of the CING, December 10th to December 12th 2018.

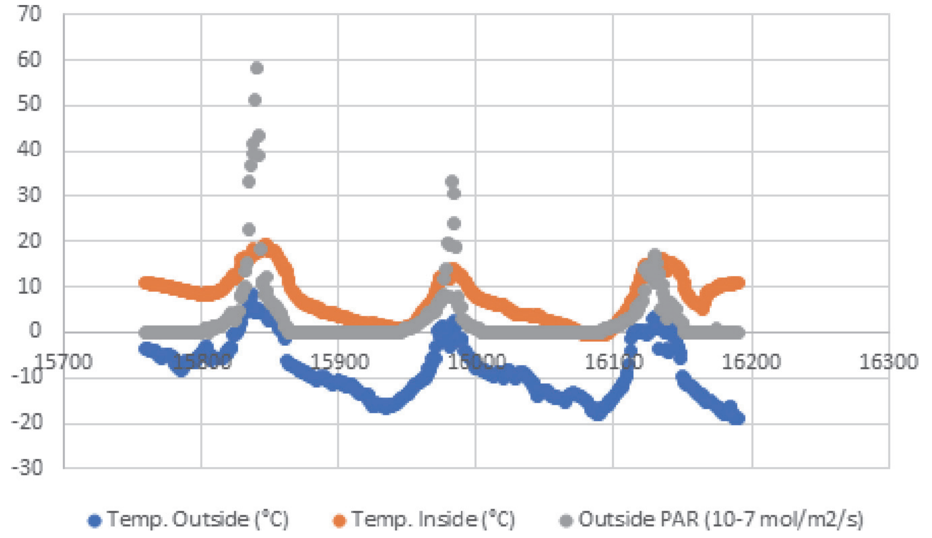

Figure 16.
Outside temperature, inside temperature and outside PAR of the CING, march 4th to march 6th 2019.

Fall trial and R^2 = 0.702 for the Winter trial during the 3 days comparison and R^2 = 0.3114 for the Fall trial and R^2 = 0.5741 for the Winter trial during the full trials.

4.3.2 Energy usage

Considering that the average cold and warm weather maximum energy requirements of the CING are approximately 21.7 kWh.m^{-2}, the maximum yearly energy use of the CING would be 7920 kWh.m^{-2}. This is still considerably higher than the modified shipping container described by The University of Arizona and higher than the 711.91 kWh.m^{-2} average for 164 greenhouses occupying a total of 16444 m^2 operated by Cornell University's Agricultural Experiment Station in New York [6].

The use of the thermal curtain showed an effect on inside temperature, but the extra sunlight SHG did not provide enough light and heat to achieve growing parameters during the Fall trial. The use of electrical lights and heating however provided enough light and heat to achieve growing parameters during the Winter trial.

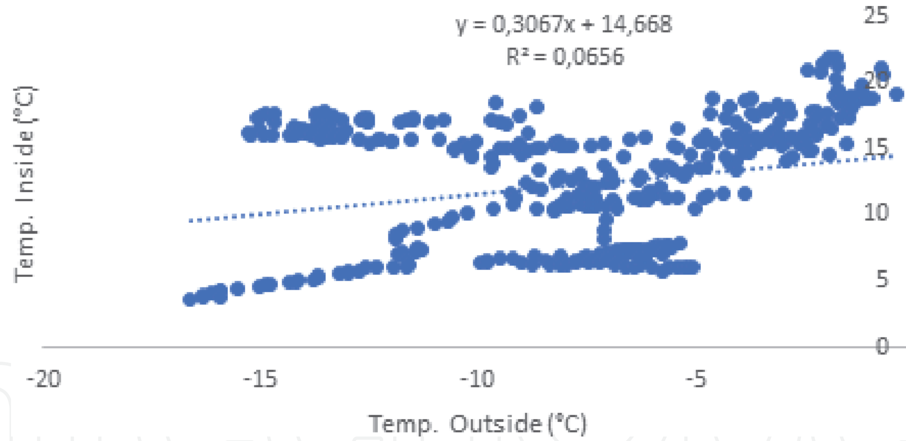

Figure 17.
Temperature inside vs. temperature outside of CING, fall trial, December 10th to 12th 2018.

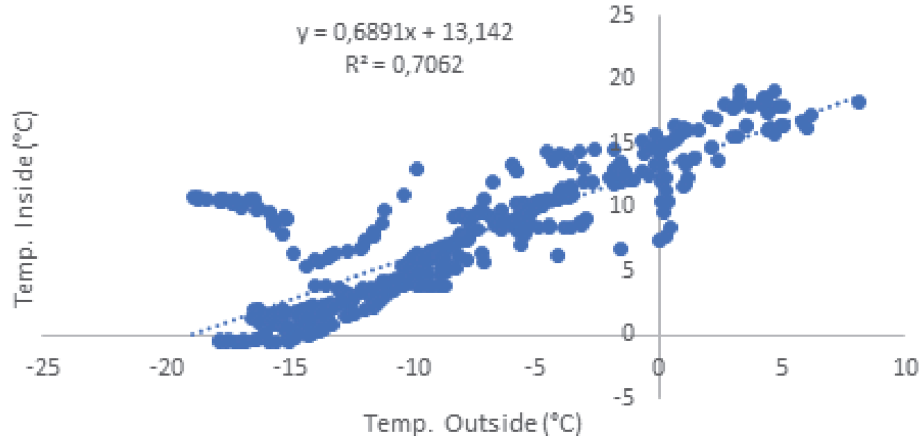

Figure 18.
Temperature inside vs. temperature outside of CING, winter trial, march 4th to 6th 2019.

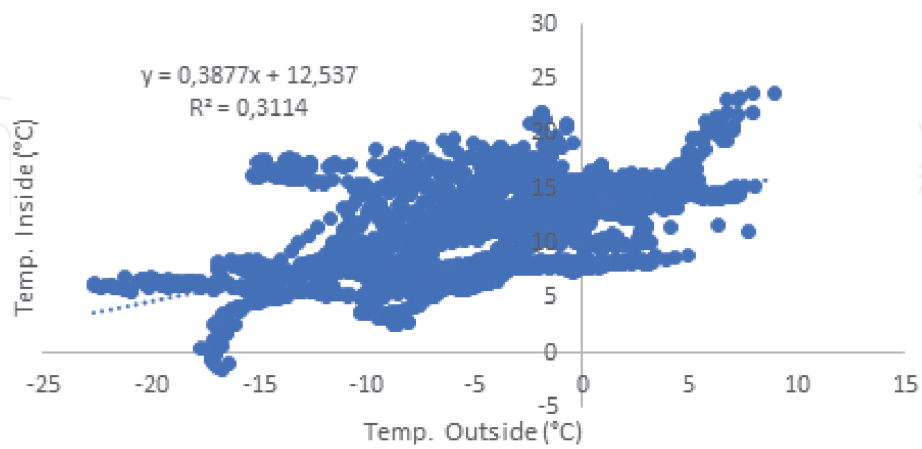

Figure 19.
Temperature inside vs. temperature outside of CING, fall trial, December 1st to December 22nd 2018.

Heating was almost constant in cold conditions, with an average indoor temperature for the Winter trial of 14.8 °C. Heating was the most energy-intensive parameter of the CING, representing 62% of the maximum daily energy requirement, but the achieved temperature was still lower than the recommended temperature for lettuce growth [10].

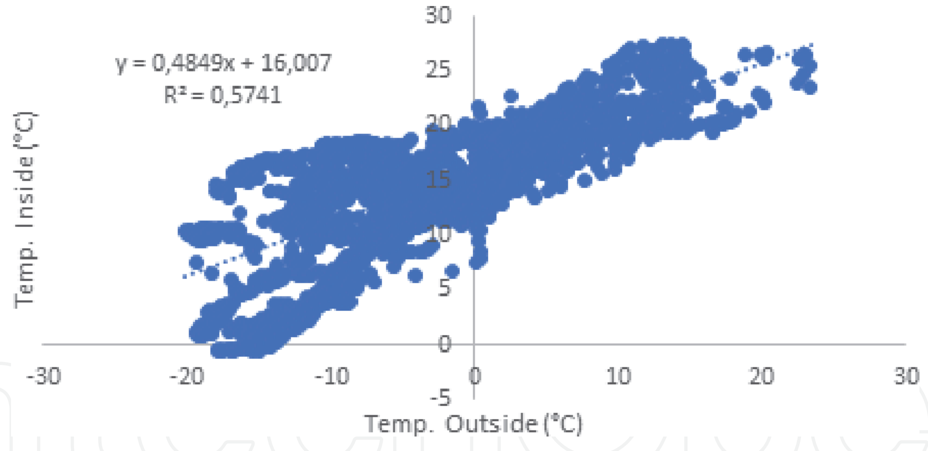

Figure 20.
Temperature inside vs. temperature outside of CING, winter trial, march 1st to march 23rd 2019.

4.3.3 Other considerations

The CING structure was strong enough to withstand the weight of snow accumulation.

Interestingly, we observed that the highest lettuce yield for the CING-grown plants was during the Winter trial. This demonstrates the potential of winter growth within the CING.

The vermicompost-based nutrient solution has seen an improvement from the beginning of the experiments but the nutrient profile is not yet complete and provides lower lettuce yields than the Hoagland nutrient solution.

4.4 Feasibility of the CING

Inspired by container farming, the CING was designed to operate in a cold and warm climate, exemplified by the short growing season in northern Canada. The environmental conditions surrounding the CING had a major impact on its interior environment, but the ability to insulate the CING unit using a thermal curtain helped manage heat and keep stable growing conditions.

If CF can successfully allow for food crop growth in a cold climate as demonstrated by these CING trials, the prototype cannot yet be considered viable as heating demands are too high and environmental control is not adequate. However, the use of natural light has made it possible to cultivate plants in this growing environment with minimal supplemental lighting. The main issue with the CING is its capacity to keep a desired internal temperature under outdoor cold conditions. The opening of the thermal curtain did increase light intensity and allowed for a higher solar heat gain. Performance of the CING in terms of biomass production was higher when the thermal curtain remained closed during the Winter, but this result is mainly caused by the average inside temperature and DLI to be higher during this trial.

5. Conclusion

The CING unit was able to successfully grow lettuce plants in a cold climate during the Winter trial but energy demands were still very high because of heating.

The dry mass of lettuce grown in the winter achieved 72% of the average fresh mass of lettuce grown at the same time in the greenhouse. In addition, the lettuce grown in the CING during the winter had the highest fresh and dry mass when compared to the other trials in the CING unit when using Hoagland nutrient solution. The vermicompost nutrient solution allowed for lettuce growth but at a much lower yield for all trials likely due to nitrogen deficiency. Continuous supplemental LED light provided the best results for lettuce growth in the CING. The thermal curtain opening according to an outdoor solar radiation threshold did allow for more light and heat in the CING unit, reducing the correlation of inside and outside temperature, under cold outdoor conditions.

5.1 Recommendations

The combination of natural and supplemental light in CF has the potential to reduce energy needs linked to lighting. However, heat loss analyses must be made to evaluate the energy efficiency of a single transparent wall or part of a single transparent wall of a container farm in a northern Canada climate.

Secondly, trials performed in the CING only used a small part of the growing space. To decrease the energy needs per growth surface another hydroponic configuration could be used. Container farms often use stacked shallow water cultures to grow leafy greens, which allows the highest density of crop production. Considering the full growing area of the CING represents half of a 40-foot shipping container or 14.4 m^2, 75% of this the growing area or 10.8 m^2 could be used for plant growth, thus reducing energy requirements per square meter of production. More lighting and air exchange would be needed to use all the growing areas, and heating energy requirements might be reduced by the addition of supplemental lighting. Modifying the CING for better space usage could reduce energy demands per unit of crops produced.

Thirdly, a recommended modification to the CING unit would be better environmental control, with a functional HVAC system; to increase the temperature and humidity control of the CING. Plus a larger thermal mass of the northern wall of the CING; to reduce the heating requirements by increasing the passive heating of the CING [12]. A complete heat exchange simulation of the CING would be necessary to compare its performance as a northern growing unit.

Appendix A

A.1 Monitoring of systems

	GREENHOUSE											CING										
	Vermicompost Nutrient Solution					Hoagland Nutrient Solution						Vermicompost Nutrient Solution					Hoagland Nutrient Solution					
DATE	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**
2018-05-08	8.4	110.0	36.2			7.5	150.0	36.2			28.5	8.2	87.7	21.1			7.5	131.0	21.0			27.0
2018-05-09	8.4	106.7	34.6			7.3	154.5	33.0			31.0	8.3	89.2	22.3			7.5	134.2	21.4			25.0
2018-05-11	9.0	100.0	32.0			7.7	160.0	32.0			34.0	8.7	81.0	13.0			7.9	126.0	13.0			13.0
2018-05-14	9.2	100.0	32.0			7.7	160.0	32.0			34.0	8.7	81.0	13.0			7.9	126.0	13.0			13.0
2018-05-15	9.7	123.0	26.0	3.3	13.2	7.7	160.0	26.0	4.0	16.3	28.0	9.0	109.0	18.0	4.0	16.3	8.1	124.0	18.0	4.0	16.3	20.0
2018-05-16	9.2	134.0	35.0	3.0	12.2	7.9	168.0	34.0	3.5	14.2	35.0	8.9	112.0	14.0	3.8	15.4	8.1	126.0	14.0	3.8	15.4	22.0
2018-05-17	9.1	141.0	27.0	2.9	11.8	7.9	183.0	27.0	3.4	13.8	28.0	9.0	116.0	21.0	3.9	15.9	8.3	127.0	21.0	3.8	15.4	22.0
2018-05-18	9.3	134.0	33.0	3.5	14.2	8.2	172.0	32.0	3.5	14.2	27.0	9.1	126.0	24.0	3.6	14.6	8.4	123.0	23.5	4.3	17.3	28.0
2018-05-21	9.3	153.0	32.0	2.8	11.4	8.3	216.0	31.0	2.2	8.9	29.0	9.0	135.0	19.0	3.4	13.8	8.3	129.0	18.0	3.8	15.4	22.0
2018-05-22	9.2	131.0	28.0	3.7	15.0	8.3	133.0	26.0	4.0	16.3	28.0	9.1	135.0	24.0	3.5	14.2	7.7	100.0	22.0	5.0	20.3	20.0
2018-05-23	9.2	140.0	32.0	3.5	14.2	8.3	143.0	31.0	3.5	14.2	27.0	9.1	132.0	20.0	3.5	14.2	8.1	102.0	20.0	4.0	16.3	22.0
2018-05-24		147.0	32.0	3.5	14.2		162.0	30.0	2.5	10.2	28.0		142.0	24.0	3.3	13.2		105.0	24.0	2.8	11.2	24.0
2018-05-25		157.0	32.0	3.2	13.0	7.9	211.0	26.0	1.5	6.1	26.0	9.2	145.0	26.0	3.4	13.8	8.3	110.0	24.0	1.3	5.3	26.0
2018-05-28	9.0	131.0		4.0	16.3	7.7	110.0		3.0	12.2			131.0		4.3	17.3		115.0		4.5	18.3	24.0
2018-05-29		141.0	32.0	4.0	16.3		121.0	28.0	2.0	8.1	23.0		136.0					115.0				
AVERAGE	9.1	129.9	31.7	3.4	13.8	7.9	160.2	30.3	3.0	12.2	29.0	8.9	117.2	20.0	3.7	14.9	8.0	119.5	19.5	3.7	15.1	22.0

Table A-1.
Monitoring of pH, EC, temperature and volume of nutrient solution for the Spring trial.

	GREENHOUSE											CING										
	Vermicompost Nutrient Solution					Hoagland Nutrient Solution						Vermicompost Nutrient Solution					Hoagland Nutrient Solution					
DATE	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**
2018-06-12	7.1	176.0	26.8	2.5	10.2	7.3	191.0	27.3	2.0	8.1		6.8	127.0	24.0	5.5	22.4	6.7	138.0	24.0	5.3	21.3	
2018-06-13	6.9	144.0	27.1	4.3	17.3	7.1	158.0	27.1	4.6	18.7		6.8	131.0	27.0	5.0	20.3	6.8	141.0	27.0	4.9	19.9	
2018-06-19												6.2	135.0				6.4	134.0		5.3	21.3	
2018-06-21	6.1	131.0		4.0	16.3	6.1	135.0		4.0	16.3		6.1	134.0		5.5	22.4	5.9	136.0		6.0	24.4	
2018-06-26	6.2	142.0	25.2	3.8	15.2	6.2	141.0	24.9	4.0	16.3		6.3	133.0	27.1	4.8	19.3	6.1	136.0	26.3	5.5	22.4	
2018-06-28	5.9	111.0		4.0	16.3	5.9	109.0		4.5	18.3		6.0	111.0	26.9	6.3	25.4	5.9	109.0	26.5	7.8	31.5	
AVERAGE	6.4	140.8	26.4	3.7	15.0	6.5	146.8	26.4	3.8	15.5		6.4	128.5	26.3	5.4	22.0	6.3	132.3	26.0	5.8	23.5	

Table A-2.
Monitoring of pH, EC, temperature and volume of nutrient solution for the Summer trial.

	Vermicompost Nutrient Solution					Hoagland Nutrient Solution						Vermicompost Nutrient Solution					Hoagland Nutrient Solution					
DATE	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**
2018-12-01	6.9	95.0		3.5	14.2	6.6	123.0		4.0	16.3		6.8	80.0		2.0	8.1	6.5	130.0		2.5	10.2	
2018-12-04	8.1	105.0	22.8	3.0	12.2	6.9	133.0	22.7	3.5	14.2	22.0	7.4	47.0	11.9	4.5	18.3	7.1	63.0	11.6	6.0	24.4	13.9
2018-12-04	7.2	110.0	22.4	3.0	12.2					0.0						0.0	6.6	129.0	11.7	6.5	26.4	13.9
2018-12-05	7.0	117.0	22.2	3.0	12.2	7.0	128.0	22.9	3.0	12.2		7.0	58.0	8.5	5.0	20.3	7.0	130.0	8.4	6.0	24.4	10.0
2018-12-10	7.0	107.0	23.1	3.0	12.2	6.7	120.0	19.9	3.0	12.2		6.9	67.0	9.0	4.5	18.3	6.9	134.0	9.1	5.0	20.3	13.3
2018-12-11	7.5	117.0	21.6	2.5	10.2	7.2	130.0	21.9	2.5	10.2	20.2	7.7	73.0	7.0	4.8	19.3	7.0	137.0	7.4	6.0	24.4	8.9
2018-12-13	6.5	122.4		3.0	12.2	6.3	93.5		3.0	12.2		6.5	57.8	11.1		0.0	6.1	105.3	8.8	5.5	22.4	16.1
	6.5	125.0		3.0	12.2	6.0	125.8		4.0	16.3		6.6	71.8			0.0	6.0	136.4			0.0	
2018-12-17	6.6	93.9	21.3	4.0	16.3	6.5	105.5	19.2	4.0	16.3	18.8	6.7	74.1	13.3	4.0	16.3	6.2	151.6	11.9	5.0	20.3	15.6
2018-12-18	6.9	95.0	23.9	4.0	16.3	6.5	112.0	23.8	4.0	16.3						0.0				4.0	16.3	
2018-12-21	6.5	116.9	23.2	3.0	12.2	6.5	113.4	22.8	2.5	10.2		6.9	84.9	13.8	3.0	12.2	6.3	165.3	12.4	4.0	16.3	15.0
AVERAGE	6.9	109.5	22.6	3.2	12.9	6.6	118.4	21.9	3.4	12.4	20.3	6.9	68.2	10.7	4.0	10.3	6.6	128.2	10.2	5.1	18.7	13.3

Table A-3.
Monitoring of pH, EC, temperature and volume of nutrient solution for the Fall trial.

DOI: http://dx.doi.org/10.5772/intechopen.96214

	GREENHOUSE													CING												
	Vermicompost Nutrient Solution						**Hoagland Nutrient Solution**							**Vermicompost Nutrient Solution**						**Hoagland Nutrient Solution**						
DATE	**pH**	**Tds (ppm)**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**Tds (ppm)**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**	**pH**	**Tds (ppm)**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**pH**	**Tds (ppm)**	**EC (ms/m)**	**T_solution (°C)**	**Level (inch)**	**Volume (L)**	**T_amb (°C)**
2019-03-02	5.6	737.0	140.0	22.7	3.0	12.2	5.6	676.0	128.4	22.1	3.0	12.2		7.6	705.0	134.0	15.0	3.0	12.2	7.2	602.0	114.4	14.6	3.0	12.2	
2019-03-05	4.2	783.0	148.8	26.0	2.8	11.2	2.5	805.0	153.0	25.2	2.0	8.1				0.0										
	4.3	674.0	128.1		3.5	14.2	4.3	680.0	129.2		2.5	10.2		6.1	567.0	107.7	5.3	2.5	10.2	6.6	546.0	103.7	6.6	2.8	11.2	11.1
2019-03-06	4.3	599.0	113.8	23.7	5.0	20.3	4.7	515.0	97.9	24.2	3.5	14.2		7.0	697.0	132.4	20.3	5.0	20.3	7.1	575.0	109.3	20.0	5.0	20.3	
2019-03-11	5.3	671.0	127.5	21.4	4.8	19.5	4.8	362.0	68.8	18.6	3.5	14.2		7.3	910.0	172.9	25.0	2.3	9.1	7.3	792.0	150.5	23.5	2.5	10.2	
														7.8	649.0	123.3		4.5	18.3	7.4	662.0	125.8		3.0	12.2	
2019-03-14	5.1	923.0	175.4	25.8	2.3	9.1	4.9	348.0	66.1	24.9	2.0	8.1		7.6	776.0	147.4	24.2	3.5	14.2	7.4	780.0	148.2	23.9	2.0	8.1	
	5.0	770.0	146.3	22.1	4.5	18.3	4.8	269.0	51.1	23.4	4.0	16.3		7.6	705.0	134.0	21.5	5.3	21.3	7.5	522.0	99.2	20.9	3.0	12.2	
2019-03-19	4.5	889.0	168.9	24.3	2.8	11.2	5.0	168.0	31.9	21.3	2.5	10.2		7.5	961.0	182.6	24.8	4.0	16.3	7.5	815.0	154.9	24.0	2.0	8.1	
														7.5	660.0	125.4	21.0	6.0	24.4	7.5	363.0	69.0	18.0	6.5	26.4	
2019-03-25	7.8	901.0	171.2	26.0	3.5	14.2	8.0	180.0	34.2	25.2	2.0	8.1		8.0	500.0	95.0	19.5	4.0	16.3	7.8	370.0	70.3	22.0	5.0	20.3	
AVERAGE	5.1	771.9	146.7	24.0	3.6	14.5	4.9	444.8	84.5	23.1	2.8	11.3		7.4	713.0	123.2	19.6	4.0	16.3	7.3	602.7	114.5	19.3	3.5	14.1	11.1

Table A-4.
Monitoring of pH, EC, temperature and volume of nutrient solution for the Winter trial.

A.2 Temperature monitoring of the CING

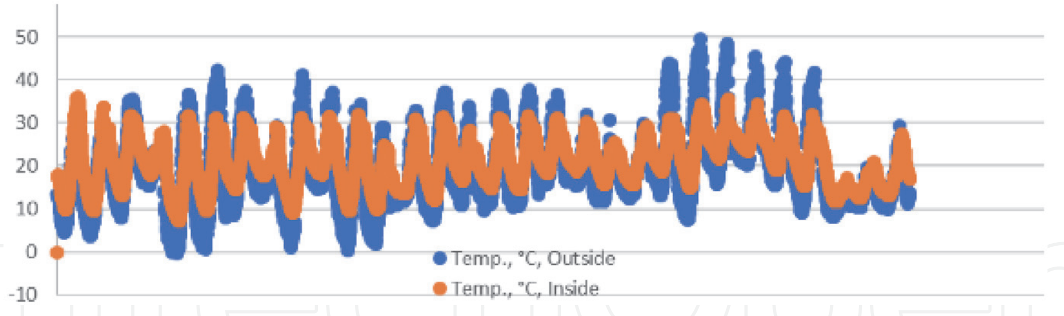

Figure A.1.
Temperature monitoring outside and inside the CING, Spring trial, corresponding averages : 19.3°C and 21.2°C.

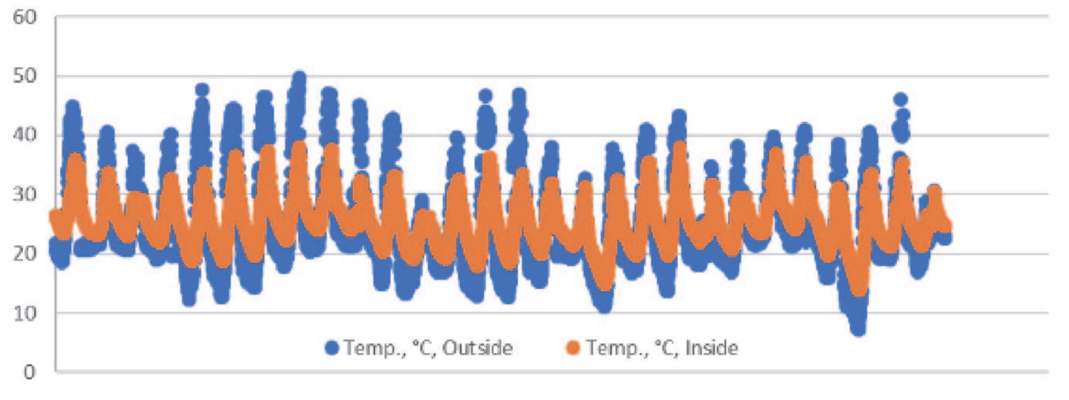

Figure A.2.
Temperature monitoring outside and inside the CING, Summer trial, corresponding averages: 24.7°C and 25.4°C.

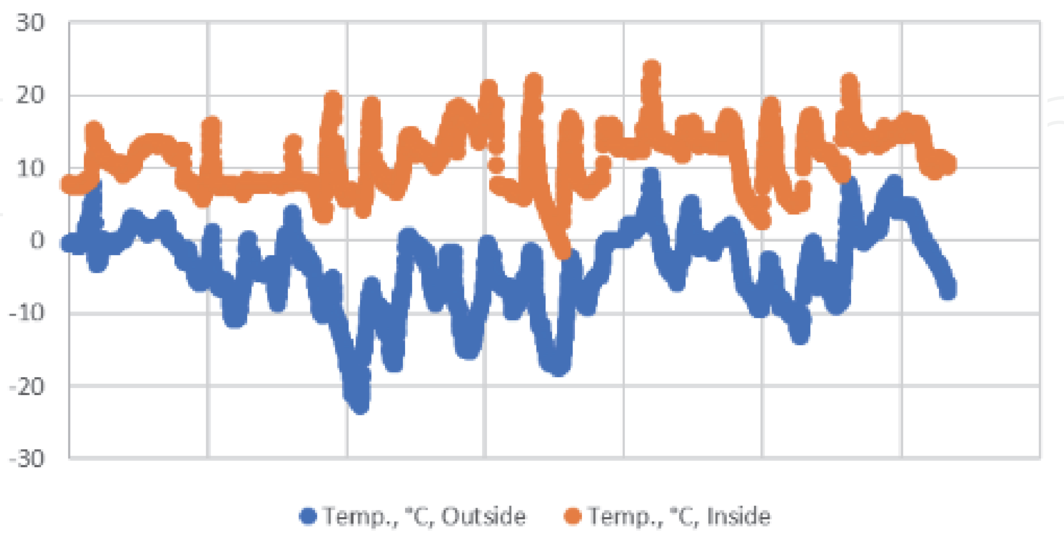

Figure A.3.
Temperature monitoring outside and inside the CING, Fall trial, corresponding averages: -3.4°C and 11.0°C.

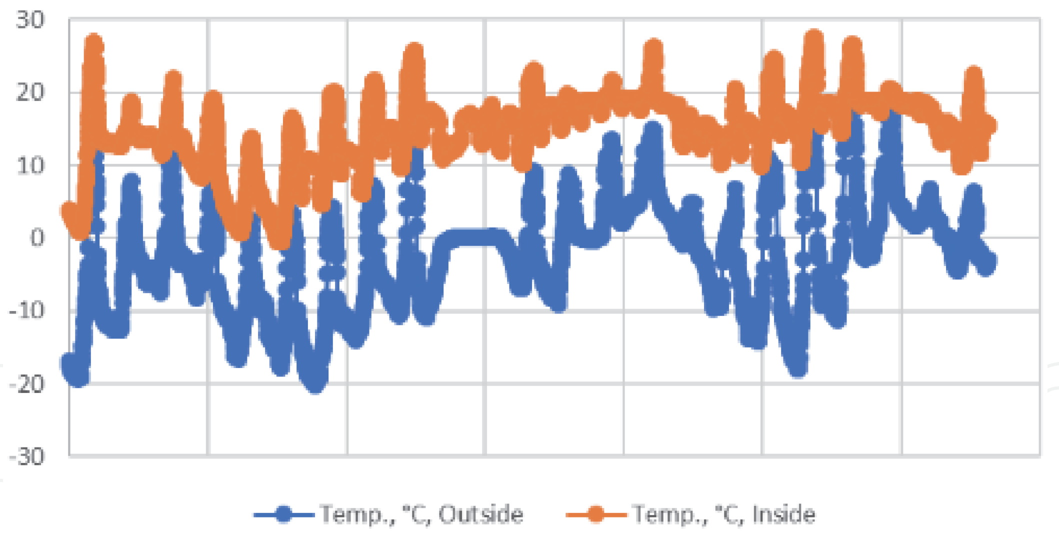

Figure A.4.
Temperature monitoring outside and inside the CING, Winter trial, corresponding averages: -2.4°C and 14.8°C.

A.3 Humidity monitoring of the CING

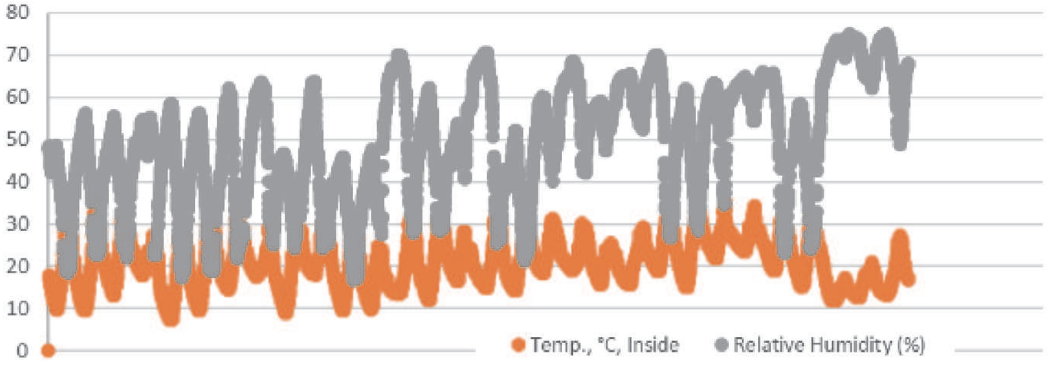

Figure A.5.
Humidity and temperature monitoring inside the CING, Spring trial, average relative humidity: 49.2 %.

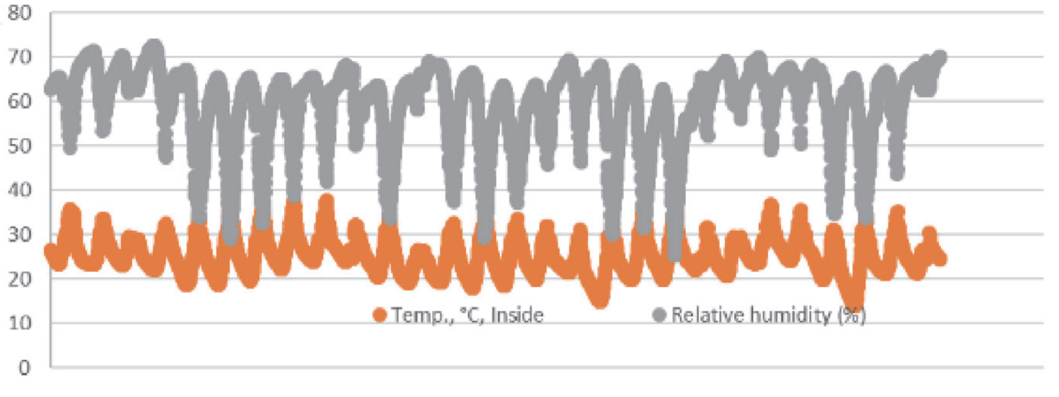

Figure A.6.
Humidity and temperature monitoring inside the CING, Summer trial, average relative humidity: 59.1 %.

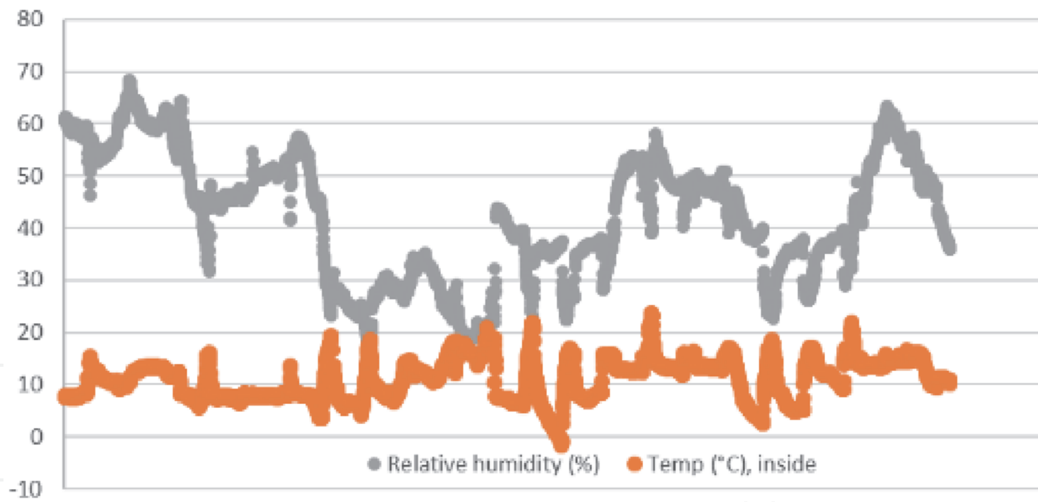

Figure A.7.
Humidity and temperature monitoring inside the CING, Winter trial, average relative humidity: 35.1 %.

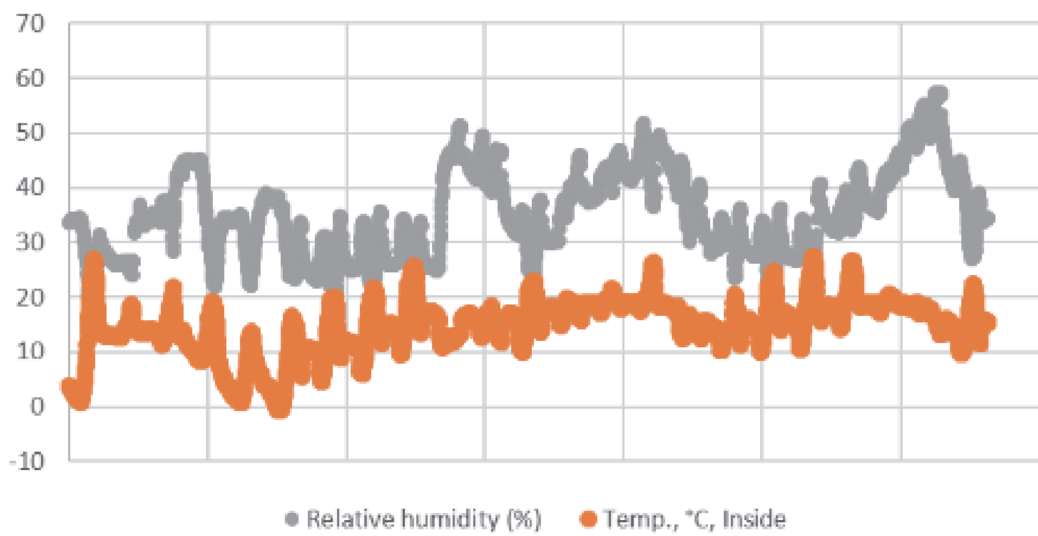

Figure A.8.
Representation of the thermal resistance of the different layers of the CING window (Bergman, Lavine, Incropera, & Dewitt, 2011).

A.4 Light mapping of systems

Experiment	Greenhouse	
Date	2018-06-19	
Time	12:20	
Weather	Very sunny	
	PAR	µmoles/m^2/s
Row	Left	Right
1	322	962
2	669	681
3	709	1077
4	937	699

Experiment	Greenhouse	
Average	659.25	854.75
Average PAR	757	

Table A-5.
Light mapping, Summer trial.

Experiment	CING	
Date	2018-06-19	
Time	12:20	
Weather	Very sunny	
	PAR	μmoles/m^2/s
	Left Row	Right rows
1	179	538
2	525	511
3	434	194
4	599	806
Average	434.25	512.25
Average PAR	473.25	

Table A-6.
Light mapping, Summer trial.

Experiment	CING	
Date	2018-06-19	
Time	14:20	
Weather	Very sunny	
	PAR	μmoles/m^2/s
	Left Row	Right row
1	276.5	259.3
2	523.2	356.7
3	802.9	531.7
4	832.6	781.1
Average	608.8	482.2
Average PAR	545.5	

Table A-7.
Light mapping, Summer trial.

Experiment	Greenhouse	
Date	2018-12-20	
Time	19:00	
Weather	Night	
	PAR	µmoles/m2/s
Row	Left	Right
1	51.6	29.14
2	43.68	43.65
3	65.87	51.87
4	86.31	81.37
Average	61.87	51.51
Average PAR	56.69	

Table A-8.
Light mapping, Fall trial, only supplemental light in the greenhouse.

Experiment	Greenhouse	
Date	2018-12-20	
Time	14:30	
Weather	Very sunny	
	PAR	µmoles/m2/s
Row	Left	Right
1	76.14	76.2
2	66.27	73.3
3	88.2	98.53
4	114.92	112.23
Average	86.38	90.07
Average PAR	88.22	

Table A-9.
Light mapping, Fall trial only.

Experiment	CING	
Date	2018-12-20	
Time	19:00	
Weather	Night	
	PAR	µmoles/m2/s
Row	Left	Right
1	48.09	63.52
2	57.23	59.76

Experiment	**CING**	
3	12.57	20.52
4	20	18.94
Average	34.47	40.69
Average PAR	37.58	

Table A-10.
Light mapping, Fall trial, supplemental light in the CING.

Experiment	**CING**	
Date	2018-12-20	
Time	15:00	
Weather	Very Sunny	
	PAR	µmoles/m2/s
Row	Left	Right
1	53.5	278
2	145.08	509
3	166.34	506.4
4	187.46	523.3
Average	138.10	454.18
Average PAR	296.14	

Table A-11.
Light mapping, Fall trial.

Experiment	**Greenhouse**	
Date	2019-03-19	
Time	13:00	
Weather	Clear sky	
	PAR	µmoles/m2/s
Row	Left	Right
1	348.10	685.70
2	598.00	536.90
3	498.50	580.60
4	638.90	670.20
Average	520.88	618.35
Average PAR	569.61	

Table A-12.
Light mapping, Greenhouse Winter trial.

Experiment	CING	
Date	2019-03-19	
Time	13:30	
Weather	Clear sky	
	PAR	µmoles/m2/s
Row	Left	Right
1	110.96	174.20
2	261.50	257.80
3	59.44	197.55
4	475.30	452.10
Average	226.80	270.41
Average PAR	248.61	

Table A-13.
Light mapping, CINGWinter trial.

A.5 Thermal curtain heat transfer rate calculation

Heat transfer rate calculation

$$q_x = \frac{T_{\infty,1} - T_{\infty,4}}{[(1/h_1A) + (L_A/k_AA) + (L_B/k_BA) + (L_C/k_CA) + (1/h_4A)]}$$

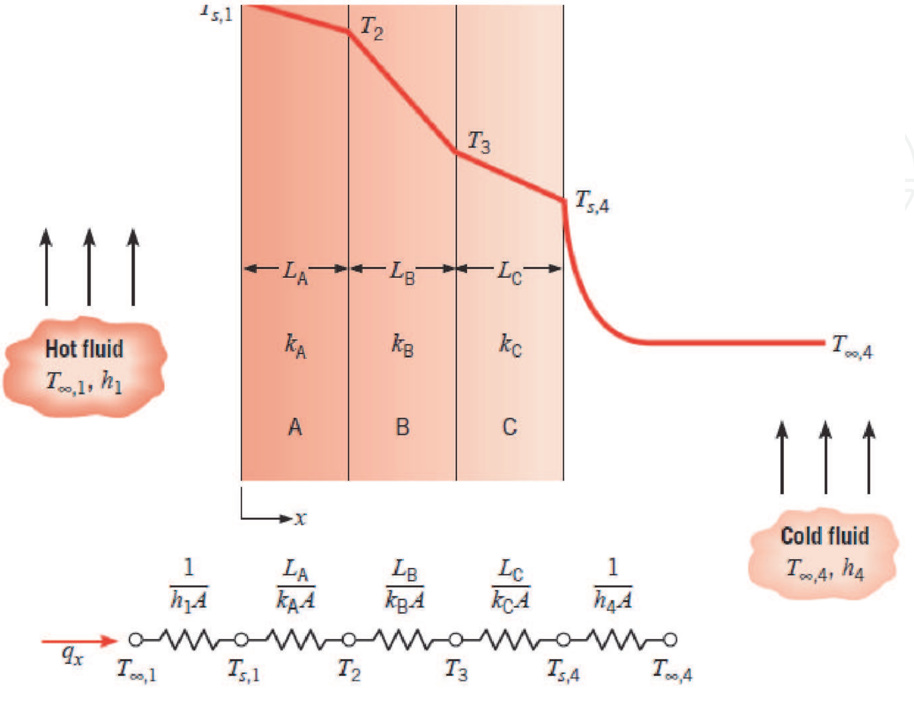

Figure A.9.
Humidity and temperature monitoring inside the CING, Fall trial, average relative humidity: 42.2 %.

Parameters	Value
Convective heat transfer coefficient of air inside CING, h_1 (W/(m^2.K)	20 (EngineeringToolBox, 2020)
Convective heat transfer coefficient of air outside CING h_4 (W/ m^2.K)	30 (EngineeringToolBox, 2020)
Thermal conductivity of thermal curtain, k_A (W/m.K)	0.104 (AZOMaterials, 2020) and (Ludvig Svensson, 2020)
Thermal conductivity of air layer, k_B (W/m.K)	$25.3\text{x}10^{-3}$ (Bergman, Lavine, Incropera, & Dewitt, 2011)
Thermal conductivity of Twin-Wall polycarbonate Sheet, k_C (W/m.K)	37.86 (PALRAM, 2010)
Thickness of Curtain, L_A (m)	0.001
Thickness of air Layer, L_B (m)	0.15
Thickness of Twin Wall polyecarbonate sheet, L_C (m)	0.008
Area of Window (m^2)	7.27
Temperature gradient, $T_{\infty,1}$ -$T_{\infty,A}$ (K)	15.0

Table A-14.
Parameters for heat transfer rate calculations.

Heat transfer rate, qx (Watts) without curtain and stagnant air layer	282.4
Heat transfer rate, qx (Watts) with curtain and stagnant air layer	17.2

Table A-15.
Heat transfer rate calculation result.

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