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Optimizing Greenhouses: A Comparative Analysis of CSB+SJU Greenhouses

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Abstract

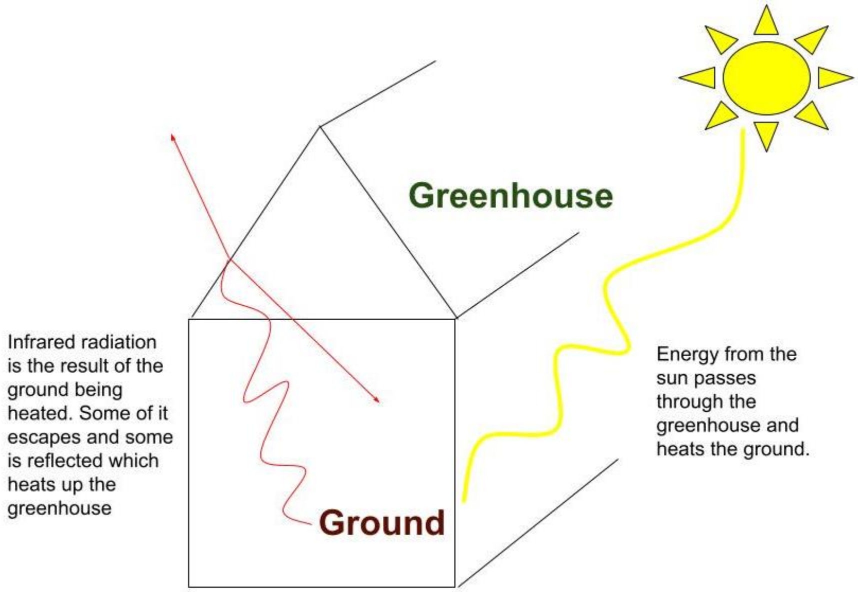
This research aims to determine the optimal design of modern greenhouses through a comparative analysis of three on campus greenhouses. Temperature and humidity measurements as well as physical observations for each site were compared to standard measurements and ideal greenhouse design components. The results of a comparative analysis allowed for the three on-campus greenhouses to be ranked against this section. The trends found in the data confirmed the findings of previous research. Recommendations for operating an optimal greenhouse derived from the analysis and observations along with suggestions for experimental improvements based on a previous study are also included.

Introduction

Greenhouses have been significantly developed over the course of human history with the earliest designs supporting the Roman emperor Tiberius' desire to have cucumbers every day and the latest designs supporting vertical farming practices that aim to ensure global food security (Bruno, 2017). The benefit of a greenhouse is that it is an enclosed growth environment for plants that can be used in climatic zones where outdoor agricultural practices are not always feasible. For much of history greenhouses have been exclusive additions to the estates of those with significant wealth and status. However, modern greenhouses rely on more affordable materials making it easier for them to be scaled down to the needs of hobbyists or scaled up to a commercial level for supplying fresh produce to local grocers. With the future of sustainable agriculture seemingly shifting to indoor growth environments due to the varying impacts of the climate crisis, studies around optimizing greenhouses are becoming more prevalent.

Much of the literature on improving the design of modern greenhouses discuss first the underlying physical relationships that allow greenhouses to function as expected. The earth's

Figure 1: This diagram provides a basic explanation of the underlying physical relationships that support the functions of a greenhouse. The diagram can be related to the earth's greenhouse effect where the greenhouse depicted represents the earth's atmosphere. The earth's atmosphere consists of 'greenhouse gases.' After the sun's radiation is absorbed by the earth's surface, the earth emits heat. Some of this heat energy passes through the atmosphere but most of it is trapped by greenhouse gases which warms the earth in the same way that the reflected infrared radiation warms the greenhouse.



greenhouse effect is characterized by absorption of shortwave radiation from the Sun that is transmitted through Earth's atmosphere and reaches the surface. Earth's surface becomes heated from this absorption and emits thermal energy as long wave (infrared) radiation which is mostly absorbed by the Earth's atmosphere rather than transmitted entirely back into space. This process effectively heats the planet causing a significant effect on its overall climate. The literature describes the short-wave radiation from the Sun as the input radiative flux density. The difference between this input radiative flux density and the total radiative flux density emitted by the Earth's surface is referred to as the Earth's radiative energy balance or budget (Schwartz, 2018). The phenomenon occurring in a greenhouse can be thought of as a scaled down version of this as shown in Figure 1.

The research outlined in this paper aims to determine the optimal design of modern greenhouses through a comparative analysis of three on campus greenhouses. It confirms previous research which found that: "indoor air temperature of a greenhouse changes with time and according to weather conditions and indoor air temperature changes after sunset" (Lee, et al., 2012). These observations led to the thermal performance of the indoor air temperature and the high transmittance of the greenhouse envelope[1] being studied in depth in the literature. The literature is primarily based on simulations of ideal greenhouse conditions in controlled settings. However, the research conducted considers greenhouses as they are being operated in real time to determine areas for improvement in overall design and design components. Observations made while conducting the current research along with data analysis of temperature and humidity measurements within each greenhouse inform recommendations for improving the performance of the three on campus greenhouses.

Methods and Materials

Three on campus greenhouses were chosen as observation sites. The EdelBrock and Grounds greenhouses are located on Saint John's campus and The Full Circle greenhouse is located on Saint Ben's campus. Background information on each greenhouse was gathered from students and staff responsible for their operation. Regular site visits were conducted to make observations on the design, components and operation of each greenhouse. Photographs were

[1] The envelope of a greenhouse is the transparent membrane responsible for allowing shortwave radiation to enter the greenhouse and trapping longwave radiation inside the greenhouse causing the increase of indoor temperature. It also acts as a shield that protects the greenhouse environment from the influence of outside weather conditions. The greenhouses studied use polyethylene film as the primary envelope with one greenhouse also featuring airbags. Polyethylene film has high transmittance (95% for longwave radiation) which means greenhouses designed with this envelope struggle to keep temperature optimal at night and require thermal storage inside the greenhouse to combat the heat loss experienced (Lee, et al., 2012).

taken using a cellphone camera and fieldnotes were recorded in a notepad and by using a voice recording application on a cellphone. Photographs were saved in a Microsoft Word document and fieldnotes were converted to tables in Microsoft Word. This information was used as the foundation for a comparative analysis that evaluated the performance of each greenhouse relative to the others and to the standard. For this experiment standard temperature for optimal greenhouse activity was considered to be within the range of 18 - 27 degrees Celsius and standard humidity 55% (Lee, et al., 2012).

The research relied heavily on data collection as such the Elitech GSP -6G data logger shown in Figure 2 which was used to record temperature and humidity measurements. Three of these devices were purchased and one was placed in each greenhouse.

Figure 2: The Elitech GSP-6G data logger with temperature and humidity sensors was used to collect data at the three sites. It was programmed using the software included with purchase that was downloaded from the company website. Using the data loggers required some trial and error to determine an ideal logging interval and the logging could sometimes be interrupted if the sensors got wet or experienced some other interference.

The layouts of the EdelBrock and Full Circle greenhouses allowed for the instrument to be centered along the back wall of the greenhouse interior. The Grounds greenhouse required that the logger be placed in the center of the greenhouse interior for accurate results. The instruments featured wired probes as sensors. To limit false readings or interruptions in the logging period due to interference with the sensors the instruments needed to be protected. The instrument in the Grounds greenhouse was most exposed. A protective case was made to block direct sunlight and keep moisture out.

Data collection was conducted over an eight-week period. The first logging period for all of the sites served as a test of the instruments and lasted one week with intervals of three minutes. The logging interval was then changed to one hour and the second logging period lasted two weeks for the EdelBrock and Full circle greenhouses. The Grounds greenhouse was undergoing renovations during the second logging period. The instrument remained set to log data every hour until the conclusion of the data collection which lasted 7 weeks. The EdelBrock and Full Circle greenhouses had a third logging period for which the instruments were set to log data every thirty minutes and this lasted 5 weeks. At the end of each logging period the devices were connected to a laptop via USB and the data was uploaded to the Elitech software application. Using this software preliminary graphs were created and saved along with the raw data. These graphs were analyzed to identify trends in the data. Then data samples were taken from the raw data and input into Microsoft Excel to create more useful graphs. The data was also averaged for each data collection period and these averages were compared to the standard temperature and humidity measurements to determine how well each greenhouse performed. Each instrument came with its own calibration tables that outline any uncertainties which were used to support analysis.

Results

In this section an overview of the data collected throughout the project is paired with explanations of how this data was impacted by external factors for each site. This section also includes a comparative analysis of the three greenhouses based on trends in the data and site observations.

Data

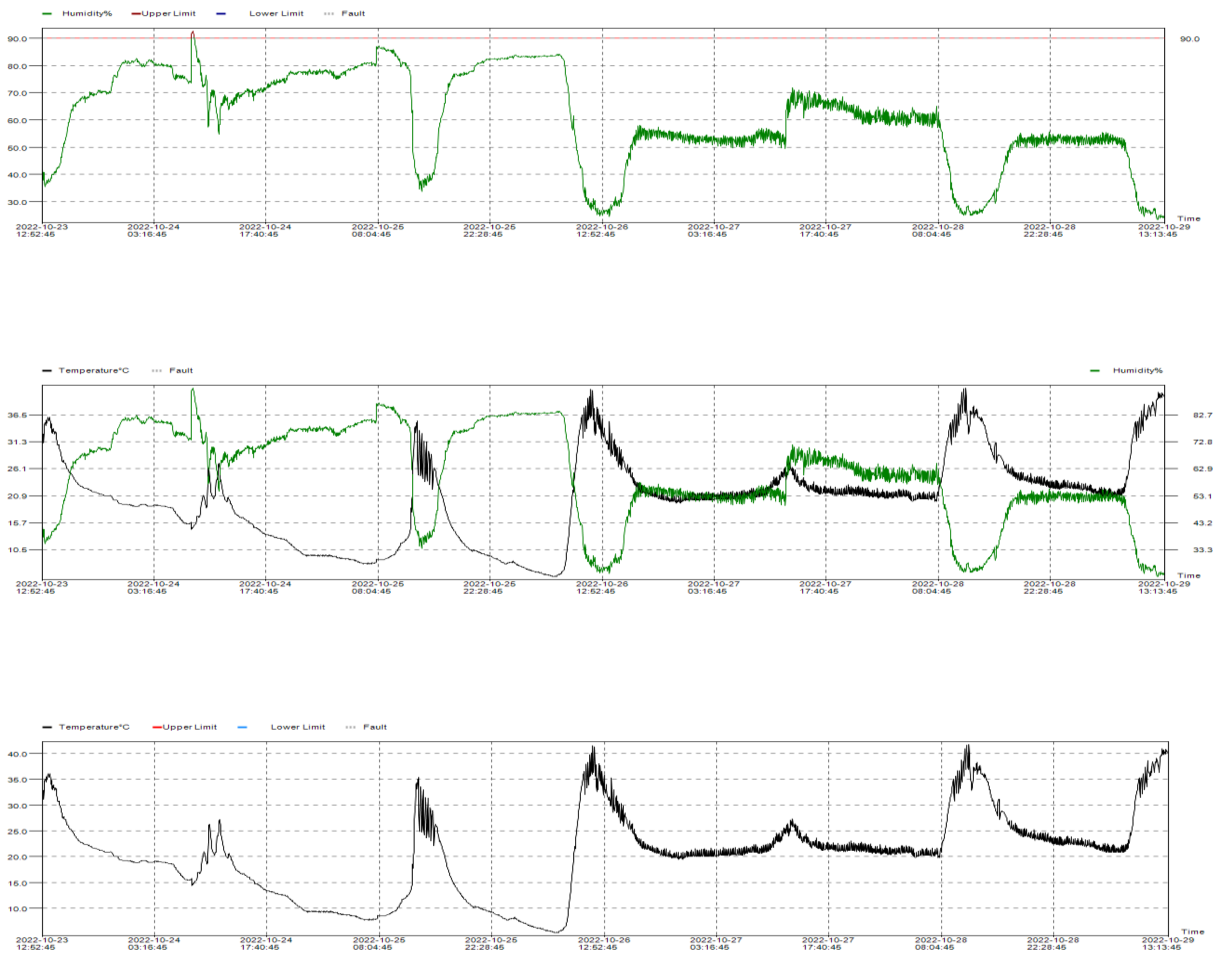
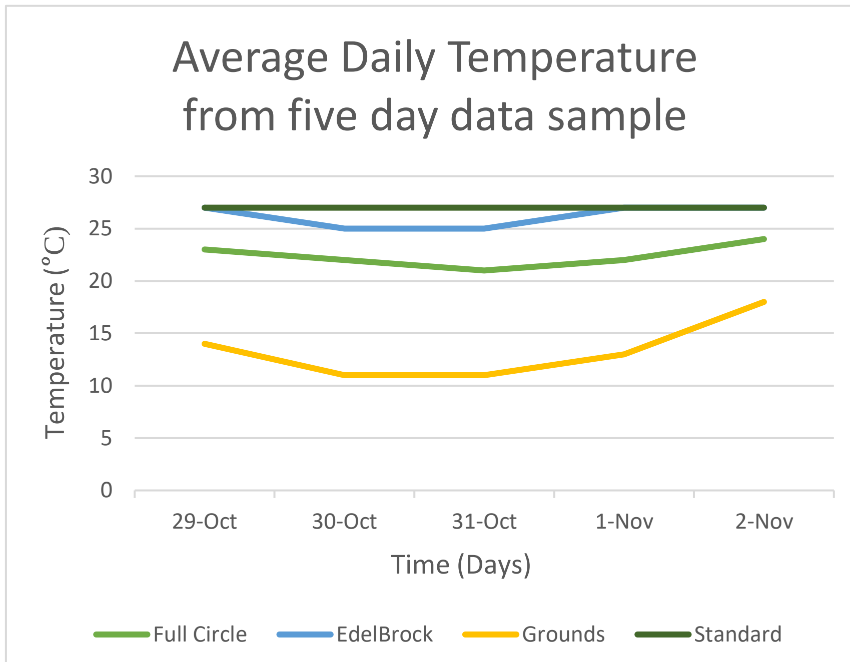


Figure 3: Temperature and Humidity Graphs produced by Elitech software from first data set collected at the EdelBrock site. The graphs produced provide a visual representation of all the data collected by the logger. These graphs were used to identify trends in the data and then the context from observations were considered to gain a better understanding of how the data was reflecting what was happening in the greenhouses. (Temperature data is in black while % Humidity is in green.)

Figure 3 provides an example of the graphical output from Ellitech Software. Specific data trends and sample periods were identified for further analysis by referencing these graphs and considering external factors affecting each site. For instance, Figure 4 and 5 show two five-day data sample periods for average daily temperature before and after the Grounds greenhouse had undergone renovations. In both data samples the Grounds greenhouse did not compare well with the standard. However, calculating the standard deviation of temperature measurements for the Grounds greenhouse before and after the renovations were completed revealed that there was significant improvement. Before the renovations, the standard deviation was found to be 7.4 °C compared to 5.2 °C after the renovations.

Figure 4: The line graph compares the average daily temperatures of each greenhouse to the standard measurement of 27 degrees Celsius for a five-day data sample. EdelBrock shows the least deviation while Grounds shows the most. This agrees with observations since this data sample was taken before the renovations to the Grounds greenhouse. Moreover, the EdelBrock greenhouse is described as state-of-the-art and cost a total of $124,000 to construct compared to the grounds greenhouse that is at least 15 years old and costs closer to $20,000 to construct. The full circle greenhouse deviated a fair amount from the standard but still performed significantly better than Grounds



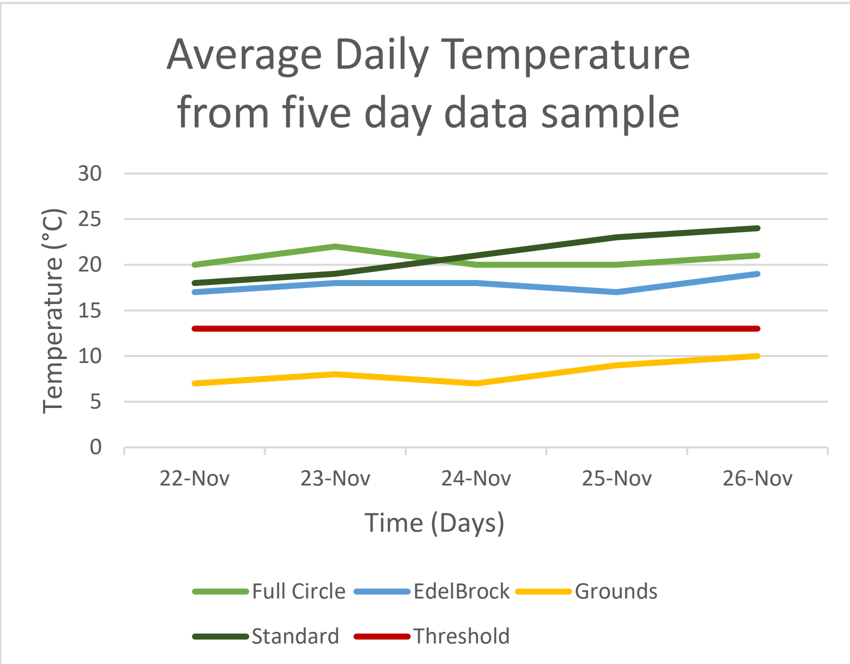


Figure 5: In the winter, the optimal operation temperature range for a greenhouse is 18-24 degrees Celsius. A threshold at 13 degrees Celsius is represented in red on the line graph indicating that temperatures below this threshold would be dangerous for plants. This graph compares average daily temperatures of each greenhouse to the optimal temperature range for winter. The data was taken from a sample recorded after renovations on the Grounds greenhouse were completed. The Full Circle and EdelBrock sites compared well to the standard, but Grounds was below the threshold.

It's not surprising that the Grounds greenhouse was below the threshold because there were no plants being housed in the greenhouse. Plant density is a factor that contributes to both temperature and humidity regulation inside a greenhouse (Lee, et al., 2012). Figure 6 offers insights on how the plant density in each greenhouse impacted the temperature and humidity measurements.

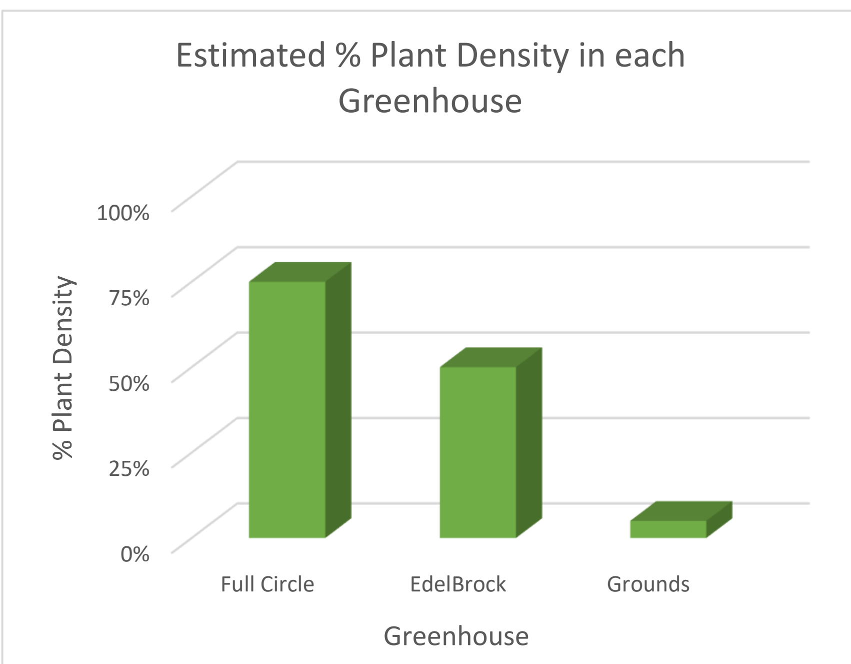


Figure 6: The Full Circle greenhouse had the highest plant density because it featured hanging planters in addition to the ground and wall space used for planting. EdelBrock had the second highest plant density relying only on a slightly larger ground planting area than Full Circle. Due to the damage (see Figure 8), there were no plants being grown in Grounds during the data collection period.

The Full Circle site showed improved temperature readings during its harvesting phase (this phase was later in the data collection period, see Figure 5) compared to the planting phase (which was earlier in the data collection period, see Figure 4). This improvement corresponds to an increase in the plant density and confirms a relationship between plant density and temperature regulation inside a greenhouse.

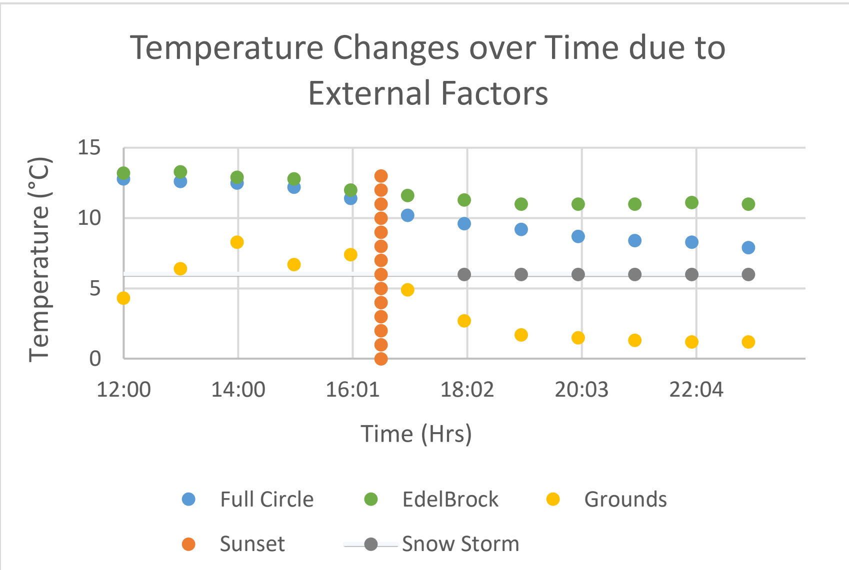


Figure 7: This scatter plot illustrates how external factors (sunset, weather conditions) impact the indoor air temperature of each greenhouse site. For all sites, the data shows a trend of temperature decreasing after sunset at 4:32 p.m. (Time & Date, 2022). These lower temperatures coincide with a snowstorm that began on the evening of December 12th which is the day this data was recorded. (NWS, 2022).

The data also confirmed findings from previous research. Figure 7 shows how indoor air temperature of each greenhouse changes over time and due to weather conditions. It also shows that indoor air temperature of each greenhouse significantly decreases after sunset.

Comparative Analysis

A combination of design components and insight from data collection for each greenhouse was used to compare the three sites and determine which is closest to an ideal greenhouse. In Table 1 an outline of design and operation elements is provided. The EdelBrock and Full Circle greenhouses are the same style both featuring the south facing paneled wall & roof that maximizes sun exposure for the planting area. Conversely the Grounds greenhouse has a more traditional style featuring a fully paneled roof that allows for a lot of sun to enter the greenhouse but can have adverse effects on growth because this sunlight is less directed to any specific growing area.

Additionally, the Grounds greenhouse has a much larger space compared to the other two greenhouses which means temperature and humidity control is more difficult. Two other features that give EdelBrock and Full Circle the advantage over Grounds for temperature and humidity control are the two door entry systems and large water bins. Storing large water bins at the back of the greenhouses helps to control greenhouse conditions after sunset because during the day the water stores heat and releases it overnight when temperatures inside the greenhouses drop. The two-door entry system helps to reduce the influence of the outside air conditions on the inside air conditions of the greenhouse.

Greenhouse	Grounds	EdelBrock	Full Circle
Location	SJU	SJU	CSB
Operated by	Aiden Shoberg, Grounds crew	SJU Eco houses	Sustainability Office Student Employees
Type	Traditional (80s/90s style), Standard household/small commercial model specific to the region	More modern + sustainable model with attached storage shed	More modern + sustainable model with attached storage shed
Roof + Walls	The entire roof is made of 8mm polyethylene sheets. Walls made of airbags with sheets along the bottom	The South facing wall and portion of the roof are made of 1cm polyethylene sheets.	The South facing wall and portion of the roof are made of 1cm polyethylene sheets.
Temperature & Humidity Control	Microgrow heating & cooling system, with overhead automatic fans	Heating/Cooling System, two door entry, large water bins	Heater, manual standing fans, two door entry, large water bins
Watering system	Overhead water distribution system, manual watering	Manual watering	Manual watering
Greenhouse Floor	Light colored concrete floor with some exposed ground	Fully exposed ground	Fully exposed ground

Table 1: This table outlines the background information of each greenhouse. It compares the design, components and operating systems of the three greenhouse sites. Grounds appears to be an outlier among the three since it is the oldest. While conducting my research I observed the Grounds greenhouse undergo renovations to the roof and walls which were worn and damaged. The other two sites are similar in design and operation which is mostly manual compared to Grounds which has automatic watering and temperature + humidity control systems.

The Grounds greenhouse is much older than the other two greenhouses and had significant damage for most of the data collection period as pictured in Figure 8. It does feature an automatic heating and cooling system, but this component was oddly positioned within the space (shown in bottom right of Figure 8).

Figure 8: These images are all of the grounds greenhouse prior to the renovations. On the left are images of the paneling that show damaged seals and discoloration. The top right shows the collapsed wall of deflated air bags. And the last image shows the temperature control system which is not central to the space.

Table 2 shows how the average temperature and humidity measurements for each greenhouse compare to the standard. The standard humidity exists as a range from 50-80% and throughout the data collection period all of the greenhouses showed results within this range. However, higher humidity is preferrable to the dryer season because if humidity is too low plants try to compensate by minimizing water loss. This reduces yield by slowing down photosynthesis. On the other hand, too much humidity directly effects the absorption of nutrients which also reduces yield (Lawson, 2023).

Planting Phase *(Earlier data collection)*	Standard/Theory	Grounds (Before Renovations)	EdelBrock	Full Circle
Average % Humidity	55	65	61	79
Average Temperature (Celsius)	27	13	20	19
Harvesting Phase *(Later data collection)*	Standard/Theory	Grounds (After Renovations)	EdelBrock	Full Circle
Average % Humidity	70	75	66	68
Average Temperature (Celsius)	18	3	13	17

Table 2: This table features some results based on the data collected at an earlier and later phase then compares them to the standard/theory measurements. The first data set featured the most data because sensors were logging data every three minutes. This dataset was collected before the greenhouses were fully operational for the growing season and the results were expected to deviate from the standard. Also, the sensor in grounds stopped taking humidity at some point because of interference from the weather. For future datasets, the sensors were repositioned and protected to limit any interference and the logging intervals were changed first to every hour then to every thirty minutes. The final dataset covered late November through mid-December, so the results reflect the outside weather conditions and with earlier sunsets lower temperatures are recorded more frequently (see Figure 7).

The standard temperature measurements range from 18-27 degrees Celsius. In the planting phase the EdelBrock and Full circle average temperatures fall within this range and Grounds is right at the threshold of plant safe temperature (see Figure 5). In the harvesting phase none of the greenhouse average temperatures fall within this range but as shown in Figure 7 indoor air temperature of the greenhouses are affected by outside weather conditions and also decrease after sunset. Full Circle had the closest to this range and this is because there weren't any additional external factors acting on this greenhouse. This was not true for the Grounds greenhouse which was in the process of being repaired for a portion of this data set (roof and walls were completely removed). EdelBrock also had an external factor impacting this dataset because the heater in the greenhouse was broken for two weeks. The inner door was left open so that the second heater in the adjoined shed space was controlling the greenhouse temperature, but this eliminated the two-door entry system.

Calculating a Greenhouse Efficiency factor

Initially, another proposed component of the research project was to calculate an efficiency factor for each greenhouse following the theory outlined in, "Estimation of an efficiency factor for a greenhouse: a numerical and experimental study," (Tiwari, et. al., 1997). In this study tedious calculations were completed using a variety of greenhouse parameters. Ultimately, the study succeeded in deriving an instantaneous thermal efficiency (η_i) which was found to increase proportional to relative humidity due to less evaporation, confirming the initial hypothesis (Tiwari, et. al., 1997). A link to a pdf of the study offering more details on the parameters and formulas is included in the Appendix.

Conclusion

According to the data, the Full Circle greenhouse shows the best performance of the three sites, and it is in the median range in terms of cost making it the best investment. EdelBrock is the most expensive build, but the Full Circle greenhouse still outperformed it because of EdelBrock's heater failure and lower plant density. The Grounds greenhouse would probably show much better results during the next growing season when plants are inside.

Recommendations

The following recommendations for operating an optimal greenhouse are based on site observations and corresponding insights from the data:

- Regular maintenance of greenhouse components (prevent failures during growing season)
- Maintain a sealed greenhouse environment (two-door entry system, proper paneling)
- Consider how to regulate greenhouse conditions after sunset (larger water bins)
- Maximize sunlight focused on the growth area (South facing wall & roof)
- Take advantage of greenhouse space (increase plant density)

Experimental Improvements

The experimental component of the research project would benefit from determining a site-specific greenhouse efficiency factor. This would require greater consideration for the parameters influencing greenhouse conditions. The study referenced earlier could be helpful with determining what those parameters are but would still be difficult to fully replicate because it relies on elements like mass of plant, transpiration and nutrient absorption rates, heat flux from heating component, solar radiation, etc.... However, one could simulate a greenhouse environment for a single plant and determine these parameters on a much smaller scale then complete the necessary calculations and compare results with those of the study.

Other considerations could include comparing temperature and humidity measurements recorded inside each greenhouse to the corresponding outdoor measurements reported during the data collection period to confirm their relationship. Also, thermal images of each greenhouse produced by a thermal imaging scanner would be a good inclusion because these images can show the areas of each greenhouse that may be affecting overall greenhouse conditions.

Appendix

Temperature and Humidity raw data:

Initial data sets - edlebrock_greenhouse_THdata.xls fullcircle_greenhouse_THdata.xls grounds_greenhouse_THdata.xls

Second data sets - edelbrock_THdata.xls fullcircle_THdata.xls

Final data sets - eb_THdata.xls full_circle_THdata.xls grounds_THdata.xls

Greenhouse efficiency factor study: greenhouse efficiency factor.pdf

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