
Proceedings Paper:

Wright, H.C., Moschopoulos, A. and Fountain, L. (2023) Design of low cost, open-source prototype plant growth chambers for evaluating crop suitability for space environments. In: Acta Horticulturae. XXXI International Horticultural Congress (IHC2022): International Symposium on Advances in Vertical Farming, 14 Aug 2022, Angers, France. International Society for Horticultural Science (ISHS) , pp. 141-148. ISBN 9789462613676

https://doi.org/10.17660/actahortic.2023.1369.17

The original publication is available at Wright, H.C., Moschopoulos, A. and Fountain, L. (2023). Design of low cost, open-source prototype plant growth chambers for evaluating crop suitability for space environments. Acta Hortic. 1369, 141-148, https://doi.org/10.17660/ActaHortic.2023.1369.17

Design of low cost, open-source prototype plant growth chambers for evaluating crop suitability for space environments.

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Abstract

Controlled environment growth chambers for evaluating growing media and crop suitability are costly and complex systems making research into these fields prohibitive for citizen science or small research groups. With a renewed interest in space exploration and research into crop growth in space, a pair of prototype open-source benchtop growth chambers with the same internal dimensions as that of the Advanced Plant Habitat on the International Space Station have been developed. The growth dimensions are 40 x 40 x 40cm with a media tray insert of dimension 5 x 40 x 40cm. The chambers have two channels of LED lighting, with five white light units and four full spectrum LED units that use passive cooling and can be independently tuned using potentiometers. Temperature and humidity are not controlled by the chambers since chambers are expected to be placed in an environment where these factors are in an acceptable range for crop growth. A Raspberry Pi 4 is used for logging of environmental factors and control of irrigation events. A GrovePi+ header is used on the RPi for ease of adding and removing sensors. The growth chambers have a temperature and humidity combined sensor (AM2302), a light sensor (TSL2561) which monitors light intensity only (lux) and a pair of analogue capacitive moisture sensors which control irrigation events using a threshold media moisture level. A 5 V pump is controlled through a relay connected to the RPi and this irrigates the media using a dripper based irrigation ladder. A digital camera is also connected to the RPi to capture photos of plant growth from above. Each growth chamber costs ~GBP900 (USD1200) and a pair have been constructed such that factors between chambers can be changed and plant growth compared.

Keywords: CEA, Raspberry Pi, hydroponics, growth chambers, spaCEA

INTRODUCTION

The global food supply chain is under strain due to an increasingly urbanised population and the effects of climate change (FAO, 2015), leading to the need for alternative food production methods. Vertical farming (VF) is gathering momentum as a novel method for producing food, due to the major aim of increasing the crop yield per unit area whilst reducing nutrient and water inputs (Beacham et al., 2019). However, these benefits come at an increased start-up cost and increased energy use (van Delden et al., 2021). Crop selection/engineering/breeding is an important consideration in VF, with crops that have

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reduced non-edible biomass, increased yield, increased growth rate and ease of harvest the most ideal (SharathKumar et al., 2020).

Simultaneously there is renewed interest in space exploration with the NASA-led Artemis program looking to return humanity to the moon by the mid-2020s, and eventually on to Mars. These missions with increasing duration plan to minimise Earth reliance and it is expected that this will involve producing increasing amounts of *in-situ* grown food (Douglas et al., 2021). Amongst the multitude of challenges involved in space crop growth is the selection/engineering/breeding of crops which are optimised for growth in the space environment. This may include plant size constraints, increased yield or nutritional content, improved organoleptic considerations and/or increased degradability of non-edible biomass for degradation and resource recovery. Many of these crop traits align with those required for optimised use in VF. The advanced plant habitat (APH) on the International Space Station (ISS) has already been used to test suitability of a range of crops including lettuce, radish and most recently chilli peppers (Wheeler, 2017). Additionally, NASA has extensively invested in citizen science programs to help gain insight into crop suitability, specifically through the "Growing Beyond Earth" program (https://fairchildgarden.org/gbe/) where more than 35000 students have contributed a large number of data points on over 150 edible plants. Many of the trials were completed in small scale plant growth chambers with dimensions equal to that of the predecessor of the APH, the Veggie system. The use of such benchtop chambers can produce a wealth of data on selecting ideal environmental conditions that optimise yield of crops and allow insight into crop suitability when rooting volume and growing volume are limited.

Despite the importance of small scale plant growth chambers in this field of research they can be exceptionally expensive, often costing several thousands of dollars/pounds/euros. This limits their use to well-funded research groups and corporations that can afford to pay this high price. In contrast to this, the use of free and open source hardware (FOSH) for equipment and free and open source software (FOSS) can drastically reduce the cost of scientific tools by upwards of 85% (Pearce, 2020). Additionally, implementing FOSH principles empowers those outside of well-funded research groups, including teachers, citizen scientists and hobbyists (Oberloier and Pearce, 2018). The design of low-cost desktop plant growth chambers using FOSS/FOSH principles that log important environmental information would increase the quantity and quality of data on crop suitability for both VF and space plant growth.

This work set out to design and build a pair of low cost plant growth chambers using FOSS and FOSH principles with growth dimensions equal to those of the APH. The chambers monitor and log important environmental conditions including temperature, light, humidity and substrate moisture, and use moisture data to trigger irrigation events to reduce the number of interventions required.

MATERIALS AND METHODS

Build Detail

The main growth chamber was made from 6 mm plywood, laser cut to size and with 2mm white PVC glued to the inside faces of the chamber to reflect light inside of the chambers. Fig 22 shows (a) an external view, (b) the internal growing area and (c) internal electronics. The chambers have growing dimensions of 400 x 400 x 400mm and space for a 50 x 400 x 400mm media insert. These dimensions are the same as those of the advanced plant habitat (APH) on the International Space Station (ISS).

Two air circulating fans (90mm Arctic F9) were attached to the inside of the chamber growing area, which run continuously in addition to an extraction fan (90mm Noctua NF-A9) in the electronics compartment to ensure a steady flow of fresh air into the chamber. Nine LED units in each chamber were split into two channels; five full spectrum LED units (10W Full Spectrum PAR LED (Bridgelux 380-840nm) on one channel and four white LED units (10W Daylight White LED (Bridgelux 5500-6000k) on the second channel. Each channel can be controlled independently using manual potentiometers.

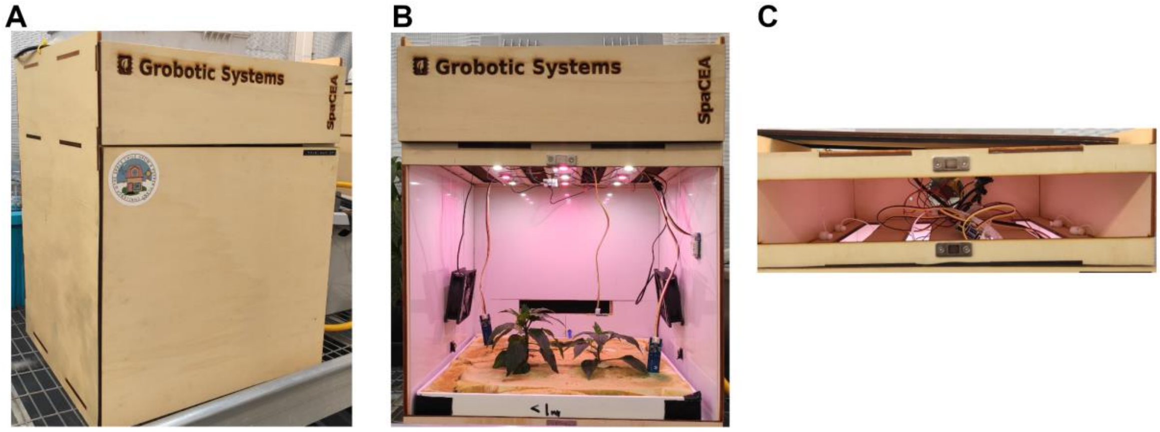

Figure 1: (A) The prototype growth chamber with the doors for the growing space and the electronics compartment on, (B) the internal grow space in the chamber and (C) the shelf for electronic components inside the growth chamber.

A Raspberry Pi 4 was selected as the platform for controlling and logging data in the chambers. A GrovePi+ (Grove SKU 103010002) bridge was used on the RPi board for ease of adding and removing sensors and to simplify the coding requirements. A AM2302 combined temperature and humidity sensor (Grove SKU 101020019) was selected for monitoring chamber temperature and humidity. A TSL2561 light sensor (Grove SKU 101020030) was selected for ensuring that chambers receive consistent illuminance over time. Two analogue capacitive moisture sensors (Grove SKU 101020614) were used to control automated watering events and log substrate moisture levels. A 5 V pump was used for irrigation, however any appropriate pump would work as long as it is able to supply sufficient pressure. A Grove relay (Grove SKU 101020005) was used to control the pump and therefore irrigation events. Finally a RPi camera module V2.1 was used to capture photographs of the chamber at set intervals. A component list and the relevant web link for each of the components used in the RPi build is given in Table 1.

A script was written in Python 3.8 to evaluate the sensors, automated irrigation and capturing of still images. The script logs temperature, humidity, illuminance and substrate moisture every 5 seconds and uses threshold values from the moisture sensors to determine if the pump should be on or off. It logs the state of the pump and captures a still frame through the camera module every 20 minutes.

Table 1: Components list and web links for further details.

Component	**Weblink**
Raspberry Pi 4	https://www.raspberrypi.com/products/raspberry-pi-4-model-b/
GrovePi + Bridge	https://www.dexterindustries.com/grovepi/
Temperature and humidity sensor	https://www.seeedstudio.com/Grove-Temperature-Humidity-Sensor-Pro-AM2302-DHT22.html
Light sensor	https://www.seeedstudio.com/Grove-Digital-Light-Sensor-TSL2561.html

Capacitive moisture sensor	https://www.seeedstudio.com/Grove-Capacitive-Moisture-Sensor-Corrosion-Resistant.html
Relay	https://www.seeedstudio.com/Grove-Relay.html
5V pump	https://www.shorturl.at/anpvJ
RPi camera module	https://www.raspberrypi.com/products/camera-module-v2/

Testing

To determine if sensor selection was appropriate, the two chambers were placed in a temperature controlled environment set to 25°C day (16hrs) / 20°C (8hrs) night temperature. Each chamber contained a different growing media (polyurethane foam or arcillite) and both contained Numex Española Improved chilli peppers. All other environmental conditions remained the same in both chambers. The two LED channels (white and full spectrum) were set to each produce 100 μmol m^{-2} s^{-1} (for a total light intensity of 200 μmol m^{-2} s^{-1}) for 12hrs a day (6am-6pm), set with a handheld PAR meter. The RPi logged environmental, light and moisture data for 100 hours, with temperature and humidity data between the two chambers being compared. The light sensor data was used to determine whether there was any drop off in light levels over time and the moisture data was used to determine the effectiveness of the automatic irrigation control system. Furthermore, insight could be gained into the effectiveness of the circulating fans at removing heat from the LEDs within the chambers.

RESULTS AND DISCUSSION

Figure 2(A) shows the temperature data for the two chambers over 100 experimental hours. The temperature rose above the daytime set point (25 °C) to ~28 °C in both chambers when the LEDs were on. The heat from the LED lights was likely causing this increase - when the lights were off, but the controlled environment remained at the daytime temperature of 25°C, both chambers cool to this set point. The two chambers were within 0.5°C of the night time set point (20°C) throughout the trial. The two temperature traces were similar for both chambers, and the mean difference between the two was 1.01°C with a standard deviation of 1.15°C. When comparing this difference to the mean temperature in the chambers it resulted in a relative standard deviation (RSD) of 4.81%. The AM2302 sensor has a temperature accuracy of ±0.5°C therefore these results were within the expected range for the sensor.

Figure 2(B) shows the logged humidity data for the two chambers over 100 experimental hours. Humidity was not controlled for in the controlled environment, however circulation should mean that humidity was similar in the two chambers as they were placed side by side. The mean humidity difference between the two chambers over the 100 hour experiment was 5.56% with a standard deviation of 3.66%. When comparing this difference to the mean temperature in the chambers it results in a relative standard deviation (RSD) of 8.83%. The AM2302 sensor has a humidity accuracy of ±2 %, indicating that slightly higher differences in humidity were observed than expected. This may be due to evaporation of water from the growing substrate or insufficient air movement from the extraction fan.

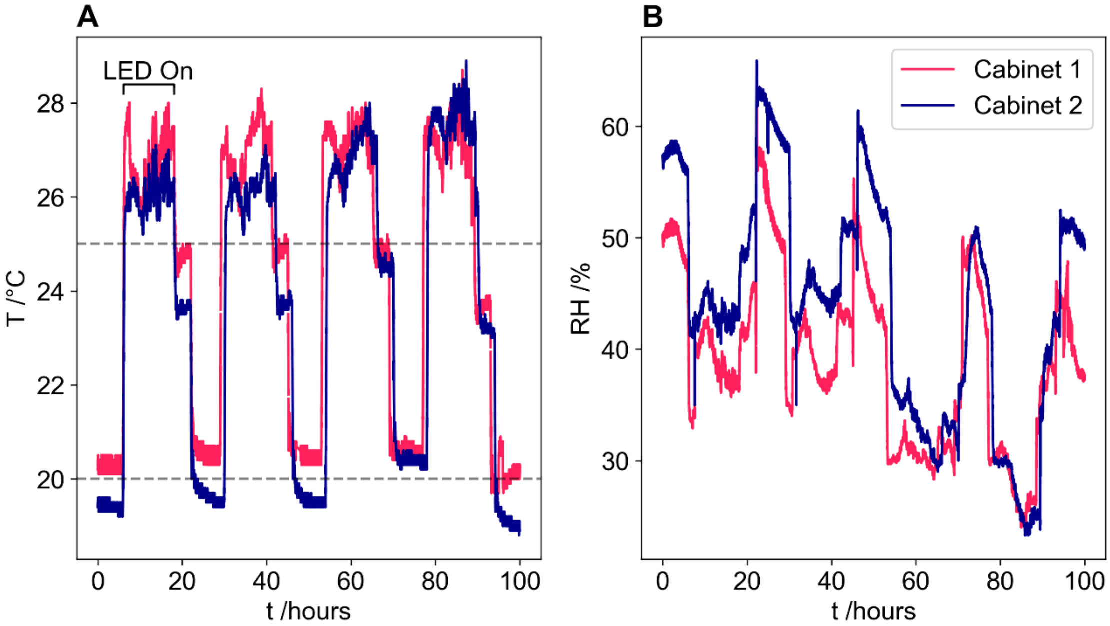

Figure 2. (A) Shows the temperature profile for the two chambers logged over 100 experimental hours and (B) shows the relative humidity of the two chambers logged over 100 experimental hours.

Figure 3(A) shows the illuminance in chamber 1 over the 100 experimental hours. The illuminance remained constant over the entire experimental period, around 16800 Lux, which it was initially set to using a WaveGo spectrophotometer (Ocean Optics). This shows that the light units did not drop off in intensity over the time frame tested. The manual potentiometers made it difficult to set the two chambers to the same light levels as they first needed to be manually set before checking in the Python response, and repeated until the final set point was reached. The use of digital potentiometers may benefit the chambers, as a light level could be set and controlled directly by the python script. This would also help if the LEDs did drop off in intensity over time, because the script could automatically adjust to account for the drop.

Figure 3(B) shows the mean reading from the two capacitive moisture meters placed in different regions of the substrate. The reading is the inverse of the moisture content of the substrate, that is the higher the value, the dryer the substrate. The horizontal lines in the figure indicate the threshold values for turning the pump on and off. The blue box at ~60 hours indicates the pump turning on and irrigating the substrate, after which the readings decreased to the off threshold and the pump turned off. The pump and moisture sensors functioned as expected. Even though two moisture meters were used, considerable variation was observed,, and using a 21 point moving average drastically reduced the noise of the readings. This will be implemented in the code in future to improve watering events. It would be of interest to be able to determine the amount of water or water-filled pore space of the substrate as well, but this would be difficult to achieve using these sensors. Further improvements could be made by introducing a flow meter or calibrating the pump in a manner that would allow determination of the amount of water/nutrient solution fed to the system in each watering event. Although the small 5V pumps worked well in this experiment, depending on the location of the reservoir they were unable to pump through porous pipe to supply water to the media on some occasions and larger pumps may be more appropriate.

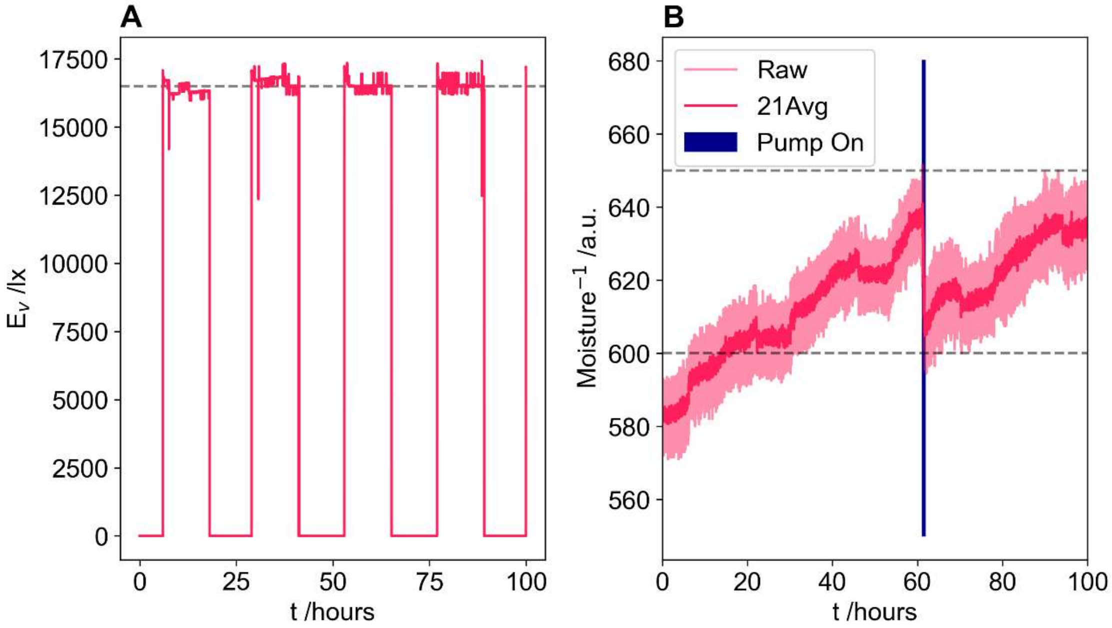

Figure 3. (A) illuminance levels in one of the chambers logged over 100 experimental hours and (B) Raw moisture content of the substrate (light pink) data with a 21 point moving average over the 100 experimental hours (dark pink) with horizontal lines showing the threshold values for triggering an irrigation event and the blue box indicating when the pump was in the 'on' state. a.u stands for arbitrary units, the signal given from the sensor.

Figure 4(A) shows basil growing in a foam substrate in one of the chambers and (B) shows chilli peppers growing in arcillite substrate in the other chamber. Both images were captured by the RPI 2.1 cameras. Although these cameras interface well with the RPi and are easy to install, they do not capture the entire growing area and a wider angle camera may provide better images. A timelapse of the basil growing in foam substrate is available here: https://osf.io/z5mr3/ (DOI: 10.17605/OSF.IO/WJ92V).

Overall the chambers performed well over the 100 hour experiment. The chambers' sensors have good reproducibility and selection was sufficient for the requirements of the project. The low cost of these sensors and good accuracy makes them ideal for citizen science projects and if additional accuracy is required, further sensors could be added. A few improvements to the prototypes could be made to improve functionality. The power of the exhaust fan could be increased to help dissipate heat generated by the LED's and to keep circulating fresh air to increase humidity stability. Digital potentiometers would make it much easier to tweak light recipes and would allow for the script to automatically correct for any drop in intensity of the LEDs. An improvement to the light sensors could also be made by incorporating an algorithm that uses the data from the LED light spectrum to convert from Lux to photosynthetic photon flux density (PPFD), a more useful light unit for growing crops.

Figure 4: (A) A still image of basil growing in a foam substrate in one of the chambers and (b) still image of chilli peppers growing in archillite growing in one of the chambers.

CONCLUSIONS

A pair of prototype low cost plant growth chambers were designed and built, and the sensors, scripts and automated watering system evaluated. The CAD-designed chamber frames were laser cut out of 6mm plywood, and the notched nature of the design makes the chamber frames easy to assemble, requiring only wood glue and clamps/elastic bands. The RPi, in conjunction with the GrovePi+ bridge, makes connection and code writing for the sensors straightforward. The temperature and humidity sensors were congruous between chambers. Temperature had a RSD = 4.81% and humidity had a RSD = 8.83%. The simple control algorithm for irrigating the media worked as intended, engaging and disengaging the pumps based on a threshold value. These prototypes revealed improvements that should be implemented in the next design, including the use of larger pumps, as the 5V pumps are insufficient in certain circumstances, the inclusion of digital potentiometers such that the system can control light recipes, and improvements to air circulation to help dissipate heat and keep humidity stable. The low cost and ease of construction makes these chambers ideal for citizen science experiments, and could help screen for optimised environmental conditions for maximum crop yield or crop varieties for growth in confined environments, including space.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Institute for Sustainable Food at The University of Sheffield and the BBSRC White Rose DTP for funding this project.

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