plant-growing facility Design and Operation

Jim C. Visschers[1,2,*]

[1] *Institut für Physik, Johannes Gutenberg Universität-Mainz, 55128 Mainz, Germany*
[2] *Helmholtz-Institut Mainz, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Mainz 55128, Germany*

Your abstract.

Contents

I. Introduction

In this work we present the design, realization and characterization measurements of a plant growing facility. The motivation behind building the plant-growing facility are planned measurements of time-resolved chiral volatile organic compound (VOC) emission measurements from plants within the lab. The growth facility is required to provide observable, controllable and importantly, repeatable growing conditions for plants in various growth stages. The growth facility needs to fulfill certain requirements in order to be used effectively for the previously mentioned experiments and to be able to facilitate in many experiment variations. For instance, individual plants should be in their individual chambers to minimize unintentional cross talk between plants and cross contamination between plants, however the ability to study plant communication through VOC emissions should be an option. Automated plant watering and day-light cycle are crucial for optimal growth conditions within a lab environment and minimize the need for outside intervention during long-running experiments or multi-week growth cycles of certain plant species. Some basic environmental parameters also need to be observed for each individual plant or compartment within the growth-chamber. These include: (1) Air temperature, (2) Air humidity, (3) Air Pressure, (4) Light levels, and, (5) Soil humidity levels. These basic measurements are needed to ensure optimal growth conditions within a compartment of the growth-chamber. By also measuring some gasses present within the growth chamber we hope to gain insight into plant conditions non directly related to the parameters previously mentioned. The desired gas concentration measurements include: (1) total volatile organic compounds (tVOC), (2) carbon dioxide, (3) nitrogen dioxide, (4) ethyl alcohols, (5) ozone, and finally (6) oxygen.

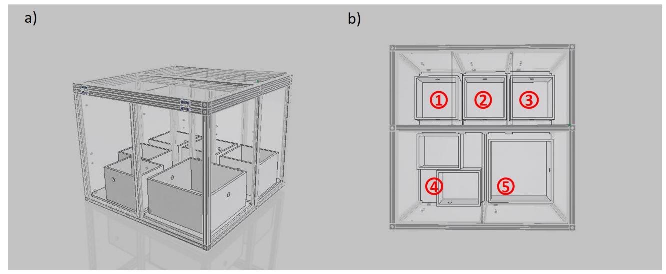

FIG. 1. Design schematics of the plant-growing facility. **a)** Perspective view of the plant-growing facility. **b)** Top view of the plant-growing facility. The different growth compartments are labeled 1 through 5. Compartments 1,2, and 3 are individual compartments allowing to house a single plants each. Compartment 4 is able to accommodate two plants with separated soil containers. Compartment 5 features a single, large soil container that can house two plants at the same time.

II. Plant growing facility

We designed a plant-growing facility consisting of five separated growth chambers, a side- and top-view of the design shown in Fig. 1. Three of the five compartments house individual plants and allow for controlled studies of individual plants. The fourth chamber houses two plants but with individual soil containers and allows for communication between two plants through VOC emissions. The fifth and final chamber in the plant-growing facility is also able to house two plants sharing the air and soil allowing for both soil and VOC communication between plants. The footprint of the complete plant-growing facility is 75 cm x 75 cm with a height of 60 cm. The soil containers have a height of 17cm. The footprint of the soil containers in the individual growth compartments (1, 2, and 3) have a size of 20 cm x 20 cm. The soil containers in the fourth compartment have a footprint of

* jvisschers@uni-mainz.de

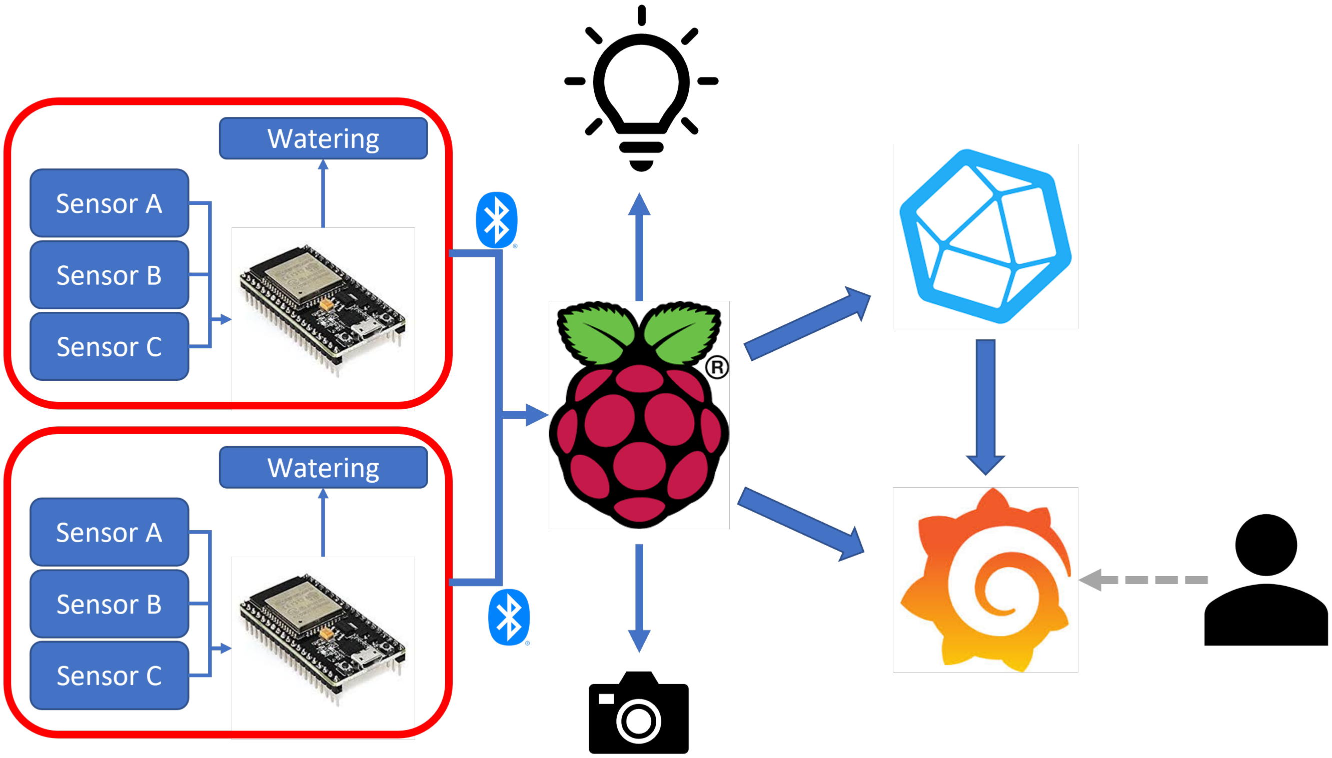

FIG. 2. Visualisation of the experimental control and data flow for the plant-growing facility. The red boxes represent individual compartments of the growth-box facility. Each functional growth chamber has an ESP-32 based sensor board which measures the climate parameters within each box and controls the watering of the soil. Each sensor board advertises the various sensor values in a Bluetooth Low Energy (BLE) service. The BLE service is read-out periodically by a Raspberry-Pi 4 which saves the data into an InfluxDB database. The Raspberry-Pi 4 also controls the light cycle of the plant growing facility and has the capabilities of controlling a camera to periodically image the growing plants. Finally the Raspberry-Pi 4 hosts a Grafana server that visualizes the data from the ESP-32 sensor boards and is remotely accessible to anyone within the institutes network.

20 cm x 16 cm, and finally, the soil box in the combined compartment has a footprint of 30 cm x 30 cm.

The frame of the plant-growing facility is made from Thorlabs optical rails while the windows and soil containers are made in-house and are made from perspex and PVC respectively. We are able to access the growth compartments in the box through two top folding doors. The first of which gives access to the three individual compartments and the second one opens up the two double compartments. Electrical access is provided through a 2 cm hole in one of the outside window panels of each individual growth chamber at the heights of the top of the soil compartments. Two smaller holes provide access for a sampling tube for sampling of the plant emissions at the top and base of the plant respectively. A final hole at the height of the top of the soil container provides access for a watering tube.

Light is provided from high-efficiency, plant growth optimized LED lighting (NEONICA Growy). The lights consume 13 W/m. The ceiling of each growth compartment is lined with 20 cm strips of LED lighting totalling 1 m. In growth chamber 3 (Fig 1b) we put an additional 0.6 m of LED lighting controlled separately form the regular lighting which gives us the ability to induce light stress in the plant growing in that compartment. To maximize the amount of light within the growth chamber we coat the insides of each compartment with aluminium foil. This subsequently limits the light leakage form the plant-growing facility [1].

III. Measurements, Data logging and handling

Structured experimental controls and a clear data collection scheme are crucial for the ease-of-use of the growth box. In an effort to retain oversight we take a top down approach: we use a Raspberry-Pi 4 to collect, store and visualize all the relevant data from the different growth compartments. Furthermore, it is in control of all -facility wide- processes (such as the light cycle). Each individual growth compartment is fitted with a home-made climate sensor that observes the relevant environmental parameters within said growth compartment and reports them to the Raspberry-Pi 4, the climate sensors also regulate processes specific to a single growth-box (e.g. watering of the plants). A visualisation of the controls and data flow is given in Fig. 2.

A. Raspberry-Pi 4

A Raspberry-Pi 4 platform is used as the main data center for the plant-growing facility. It is ideal for this specific project because it is a lightweight and affordable computer platform that supports Bluetooth Low Energy (BLE) and accommodates remote access via SSH. The Raspberry-Pi 4 is used to collect and store the sensor data from the individual growth chambers in a database. It controls the light cycle of the plant-growth facility through a USB connected relay circuit. The four relays allow for four independent light cycles within the plant growing facility. Currently the growth facility is set-up on a single light cycle and a separate relay is used to control additional lights in compartment 3 (Fig. 1) which enables us to induce light stress in that specific compartment. We make extensive use of the Linux job scheduler Cron to perform periodic tasks, such as turning on and off the lights in the plant growing facility, monitoring the climate parameters and pushing/pulling new versions of the GitHub repository.

B. Climate sensor

For the backbone of our home-made climate sensors we use an ESP-32 Development-board platform with integrated Bluetooth and Wi-Fi capabilities. It is cheaper compared to Arduino micro-controllers with similar features and is more suitable for permanent configurations as it has a smaller footprint. We designed a motherboard connecting the various climate sensors to the ESP-32 micro-controller itself avoiding electronic breadboards and jumper cables, which quickly become a mess. Figure ?? shows the schematic of the climate sensor motherboard which facilitates up-to five I^2C connections to the ESP-32 micro-controller alongside analog connections to ozone and soil humidity sensors. The motherboard also provides sockets and connections for two relay switches, one of which is used to water the plants when the soil humidity readout is below a threshold value. The ESP-32 micro-controller runs a script that reads out each climate sensor available and presents the sensor values as characteristics in a Bluetooth Low Energy (BLE) server. A readout device (client) can connect to the BLE server and subsequently read-out the various climate parameters. In our case we use the previously mentioned Raspberry-Pi 4 as a readout device, but for debugging purposes a phone using an appropriate application (e.g. nRF connect) can also be used to observe the climate parameters. The BLE server-client protocol is identical to how many wireless sports equipment works, such as, for example, heart rate chest band (BLE server) and a sports watch (BLE client).

C. Sensors

The climate sensors are equiped with various individual sensors to monitor the climate within each growth container. Table III C gives an overview of the different sensors that we fit on the climate sensor motherboard to monitor the climate within each growth container.

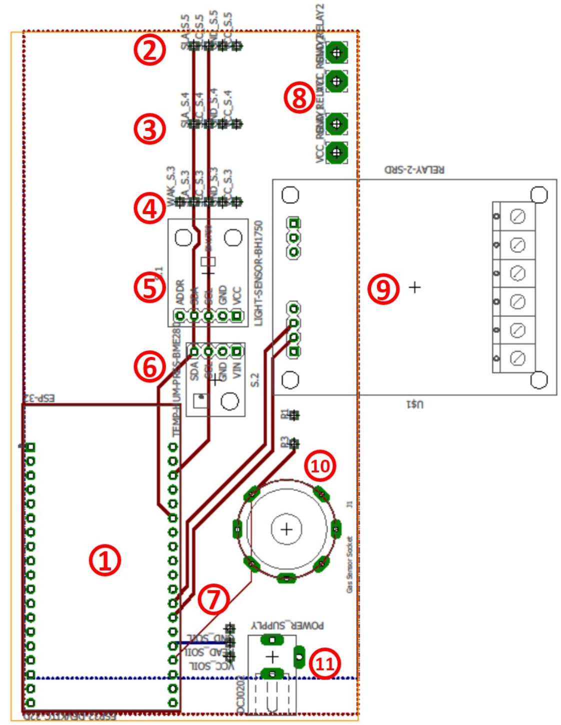

FIG. 3. Design of the climate sensor motherboard. The front and back of the motherboard have a +5V and GND plate respectively. The motherboard features the following components: (1) ESP-32 Development board, (2)-(6) I^2C connections for multiple sensor bake-out boards, (7) analog readout for a soil humidity sensor, (8) two power supplies for auxiliary components. (9) Two relay circuit bakeout board to toggle auxiliary components, (10) analog readout for ozone sensor, (11) power supply socket.

IV. Data Collection

A. Methods of Acquisition

The plant growth facility supports various methods of data collection through different channels and at different rates of acquisition. The following methods can be used for climate data collection and logging:

1. The Linux job-scheduler Cron periodically runs a homemade python script on the Raspberry-Pi 4 that reads out all the relevant sensors on each ESP-32 sensor board. The python script subsequently uploads the sensor readouts into the database where the data is stored. The maximum rate at which the Cron job scheduler is able to run the readout script is once per minute.

2. Manually running a streaming script on the Raspberry-Pi 4 to continually read out the relevant sensors on the climate sensor board. Identical to the first method the streaming script subsequently

Measurement	Sensor	Range	Type
Pressure Temperature Humidity	BME280	300-1100 hPa -40-85 ^{o}C 0-100% rel. hum	I2C
eCO2 VOC	CCS811	400-32768 ppm 0 - 29206 ppb	I2C
Light	BH175	0-65535 lx	I2C
CO NO_2 C_2H_5OH VOC	Grove-Multichannel Gas Sensor V2	∼5-5000 ppm ∼0-2 ppm ∼1-500 ppm ∼1-500 ppm	I2C
Ozone	MQ131	10-1000 ppb The other one	Analog
Soil Humidity	Capacitive Sensor	0-4096	Analog

TABLE I. Overview of the different sensors on the climate sensor motherboard. We give the measurement, type of the sensor, and the connection why which it is connected to the ESP-32 micro-controller.

uploads the received sensor values into the database for storage and remote visualisation. The streaming script can be configured to (I) readout a single climate sensor or (II) readout all available climate sensors. This data acquisition mode results in a measurement every 2 seconds, or a measurement rate of 0.5 Hz.

3. The final method of data acquisition is to connect a single sensor board to a computer and establish a serial connection. The ESP-32 boards are programmed to print the sensor values at the refresh-rate of the micro-controller firmware (~ 2 Hz). This method was originally intended for debugging the firmware of the ESP-32, however it can also be highly advantageous to see fast, dynamic changes within the growing facility. The downside of this acquisition mode it that the sensor measurements are not stored automatically in the database. Data taken through this acquisition mode needs an external program if it needs to be saved for later use.

The Cron based data acquisition method is ideal for continuous observation of the overall climate within the plant growth facility and runs continually. The two other acquisition methods are ideal for fast observation of dynamic processes in circumstances when external measurement devices are sampling within the growth chamber and these data steams have to be initiated manually.

B. Database and data visualization

We use InfluxDB as the database structure to store and handle the data from the plant growing facility. InfluxDB is an open-source database structure optimised for handling time series data. It allows high throughput data logging and native data analysis. The structure requires data to be written as JSON objects which can be added to the database. The JSON objects contain the measurement time, location within the plant-growing facility, and the respective measurement values. The database can be queried to selectively return data for subsequent analysis. To continually visualize the data stream from the growing compartments the ESP-32 sensors we use a Grafana dashboard. Grafana is an open source analytics and interactive visualization web application. It provides charts, graphs, and alerts for the growth chamber. The Grafana service is hosted on the Raspberry-Pi 4 and accessible for viewing to everyone on the institutes network accessible via IP address and port 10.106.9.83:3000.

V. Characterisation Measurements

A. Observation of gasses

Crucial for managing optimal conditions in the plant growing facility is not only the ability to observe but also the ability to distinguish gasses within each growth box. A simple validation of this fact can be seen in Fig. 4. We distinguish between human respiration and butane by identifying the temperature and humidity changes in cases of the former and absence of those same changes in the latter as both butane and respiration contain VOC's detected by the CCS811 sensor.

B. Crosstalk between growth chambers

As mentioned previously, isolation between the individual chambers in the plant growing facility is highly important to avoid plant communication. It has been widely demonstrated that plants communicate using VOC emissions. Communication between plants in separated growth chambers could be detrimental for measurement results when an affected plant is able to signal a control plant about the nature of its affliction. Therefore, isolation of each growth compartment is key. Regardless of the degree of isolation, knowledge of the permeability between the individual chambers is crucial. Figure **??** shows the leakage of methanol introduced in growth chamber 1 (Fig. 1b) at t= 0 to growth chamber 3 over more than half an hour of continuous observation. The corresponding CO_2 concentration in chamber 3 does increase, but stabilizes at a level an order of magnitude lower compared to the concentration in chamber 1. The time delay between the (possible) signalling of an affected plant to a control plant is sufficiently large to not interfere with a comparison between direct affliction and a control situation.

C. Cycle observation

Figure 5 shows the observation of two growth chambers and the ambient lab environment over a period of 36 hours. We can observe the light cycle in the growth chambers and light in the lab switching on whenever people enter in the lab. Presence of lab occupants is also seen through the rise in CO_2 and tVOC concentrations.

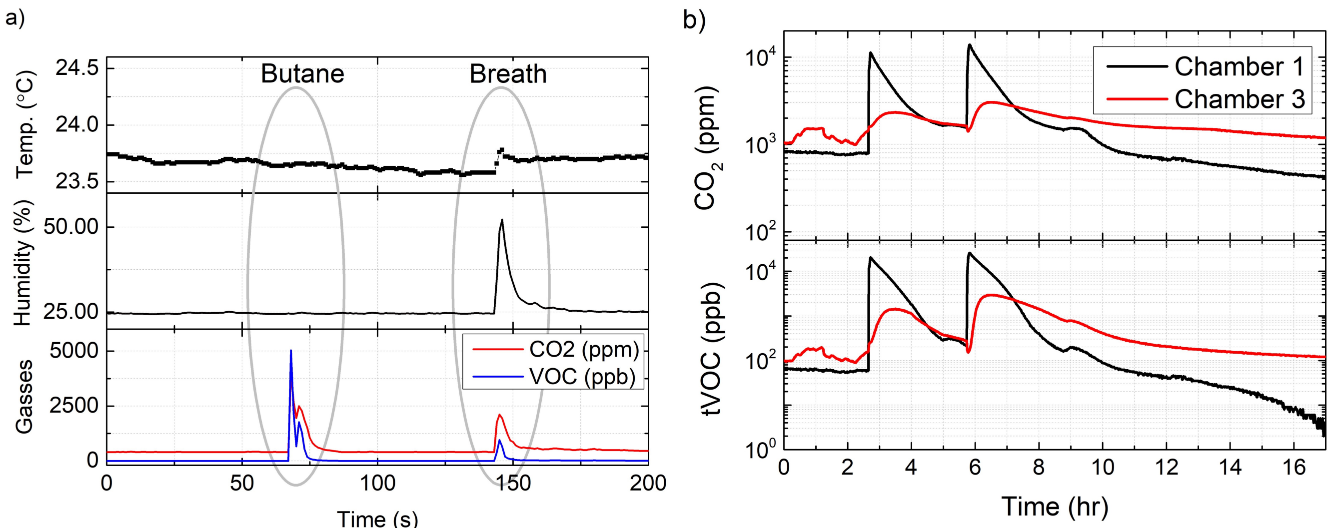

FIG. 4. Characterization measurements of the ESP32 sensor-board and plant growing facility as a whole. **(a)**. Consecutive exposures of climate sensor to butane and respiration. The butane is only registered with an increase of the measured CO_2 and tVOC concentrations by the CSS811 sensor, whereas the exhaled breath is also measured to have a higher temperature (top) and relative humidity (bottom). **(b)**. Measured CO_2 (top) and tVOC (bottom) concentrations in growth chambers 1 and 3 over a period of 17 hours. At $t = 2.7$ Hr and $t = 5.75$ Hr a petri-dish with a $\sim$ml of methanol is introduced into growth chamber 1. The CO_2 and tVOC concentrations are monitored as the methanol evaporates and diffuses through the entire growing facility. The measured CO_2 and tVOC concentrations in chamber 1 spike up immediately and slowly, over the course of a couple of hours, decay to their ambient levels. In chamber 3, the CO_2 and tVOC concentrations rise, albeitmore slowly and not as drastically as in chamber 1.The highest level of recorded concentrations measured in chamber 3 are an order of magnitude lower than the concentrations measured in chamber 1. Moreover, the time delay between the highest measured CO_2 and tVOC concentrations is approximately 45 minutes.

VI. Outlook & Conclusion

In summary this work shows a design realisation and characterization of a cost-effective plant-growth facility with integrated monitoring capabilities. We demonstrate a couple of characterizing measurements that are important for its application. Importantly, all the programs and data acquisition scripts are freely available on the GitHub development platform for future improvements and as inspiration for other designs.

[1] Much to the delight of the other occupants of the lab.

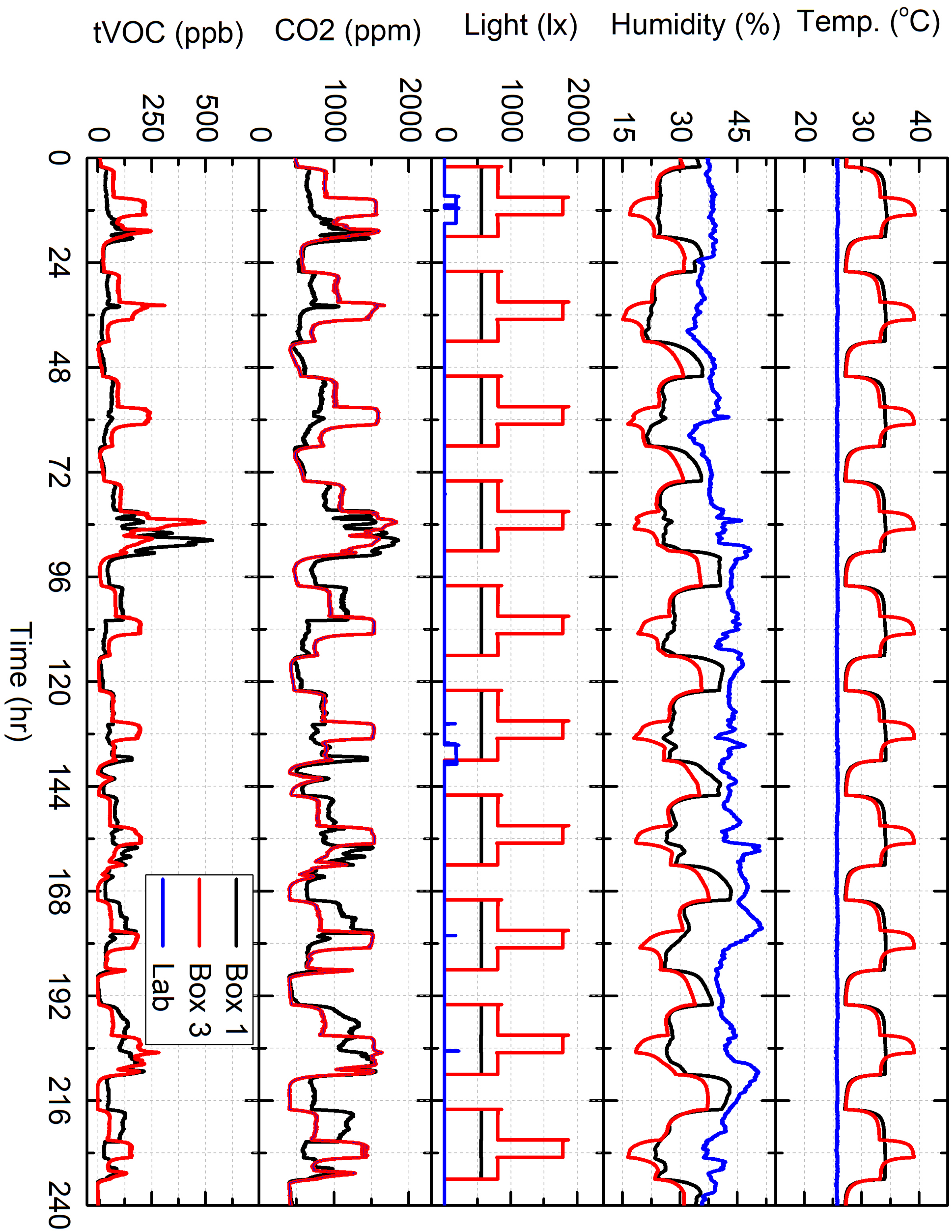

FIG. 5. Observation of the climate parameters in growth boxes 1 (Black line), 3 (Red line) and the ambient lab environment (Blue line) over a continuous period of 10 days (240 hours), starting t = 0 at 30-07-2021 00:00 until 09-08-2021 00:00. A clear correlation between the temperature and humidity within each box and the on/off status of the growing lights can be identified. Measured CO_2 and tVOC concentrations in the growth cambers are also highly correlated to the applied light cycle. Additional growing lights are turned on in box 3 for 4 hours each cycle to simulate high noon.