Final Report

Date Created: 06/13/2025

Period of Coverage: 12/11/2024 – 6/15/2025

EPA Contract #: 68HERC25C0015

Title: VerdeTerra Algae-Based HVAC Project

Principal Investigator: Mark Snyder

Entity Name: VerdeTerra LLC.

1. Executive Summary

This Phase I project explored the use of arthrospira platensis (spirulina) based photobioreactors integrated into HVAC systems for indoor air purification. Major outcomes included the successful development and operational deployment of sealed photobioreactor systems, validation of gas reduction methodologies, and the integration of BACnet-based HVAC communication. Preliminary results demonstrate promising CO_2 reduction from 5000 ppm to 1000 ppm in 15 minutes with reductions measured in NO_2, and successful simulation of commercial HVAC controls with integration into the photobioreactor system. This research enables a scalable, low-energy air purification solution for commercial buildings, particularly in healthcare, office, and institutional settings, offering measurable pollutant reduction and energy savings while integrating seamlessly with existing HVAC infrastructure.

2. Project Objectives

The primary objective of Phase I was to demonstrate the technical feasibility of VerdeTerra's Spirulina-based air purification system integrated with Heating Ventilation and Air Conditioning (HVAC) infrastructure. This system is designed to significantly reduce concentrations of indoor air pollutants including Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), and Sulfur Dioxide (SO_2), while offering potential energy savings through reduced reliance on outdoor air ventilation.

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To accomplish this, the project pursued four major objectives:

1. **Closed System Validation:** Establish a sealed experimental environment, achieving <5% leakage over a 6-hour period. This was critical for accurately measuring gas concentrations and ensuring repeatable test conditions.
2. **Pollutant Reduction Testing:** Conduct controlled experiments to evaluate the reduction of CO_2, CO, NO_2, and SO_2
3. **HVAC System Interface:** Develop and validate communication between the VerdeTerra system and a simulated commercial HVAC system using industry standard Building Automation and Control network (BACnet) and IP protocols. Demonstrate system responsiveness to pollutant levels by modulating a simulated outdoor air valve.
4. **Data Collection and Analysis:** Record, analyze, and report pollutant concentration trends, system energy consumption, and Spirulina biomass growth to inform future scaling and Phase II development.

The system's performance will be evaluated based on six criteria:

- CO_2 Air Purification Efficiency: Assess the system's ability to purify air by measuring the reduction in CO_2 pollutant concentrations using gas analyzers.
- CO Air Purification Efficiency: Assess the system's ability to purify air by measuring the reduction in CO pollutant concentrations using gas analyzers.
- NO_2 Air Purification Efficiency: Assess the system's ability to purify air by measuring the reduction in NO_2 pollutant concentrations using gas analyzers.
- SO_2 Air Purification Efficiency: Assess the system's ability to purify air by measuring the reduction in SO_2 pollutant concentrations using gas analyzers.
- HVAC Outdoor Air Valve Integration: Consistent communication established between HVAC outdoor air valve system utilization request/performance and VerdeTerra's air purification system performance.
- Bioreactor performance through
    - Energy consumption during standard operation
    - System stability and leak integrity
    - Repeatability of results across trials

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The expected outcome is a validated proof-of-concept that supports further development in Phase II, with strong indications of pollutant reduction potential, system automation, and commercial viability.

3. Technical Work Performed

3.1 System Design & Prototyping

Two photobioreactor units were constructed to accommodate internal closed-system testing, instrumentation ports, and gas circulation features. Mechanical assembly included:

- 8 Spirulina culture chambers interconnected with internal air pumping, heaters, sensors, filtration, valving, and control system. System overview shown below in **(Figure 1)**
- Silicone gas ports (inlet/outlet) are modified from commercial design to accommodate a sealed experimental system. Utilizing external air injection system and sensor package. Sealed environment overview is shown below in **(Figure 2)**
- Air injection tubing from sealed system into each of the 8 - 3in diameter algae bioreactor tubes. The air injection used varied bubble sizes to evaluate their impact on algae growth. Photobioreactor air injection pump layout described in **(Figure 2)**
- Simulated corporate HVAC system with photobioreactor communication to test and develop integrations. HVAC testbed and system layout described below in **(Figure 3)**

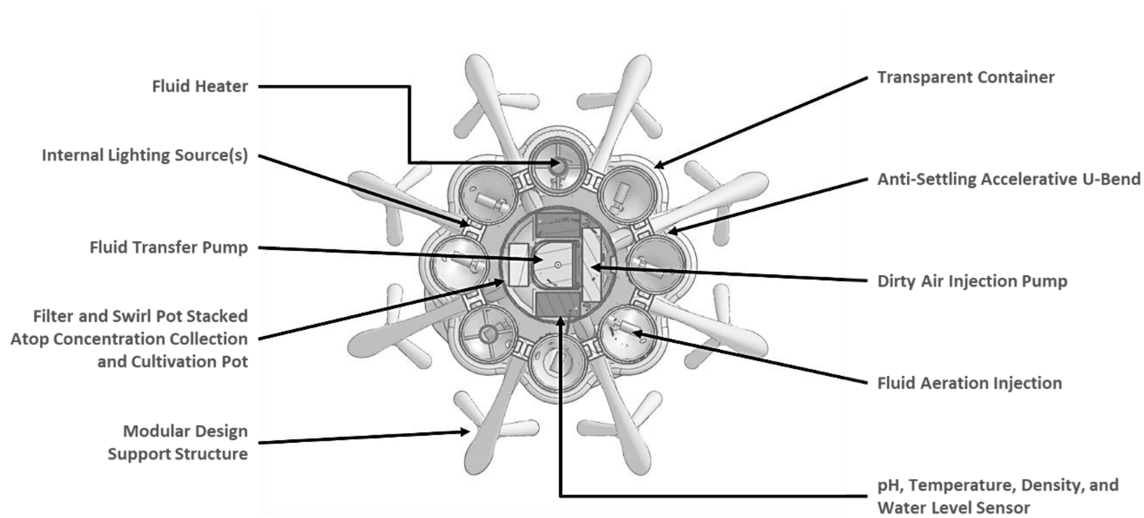

Figure 1: Albero photobioreactor top-view cross section, showing 8 perimeter photobioreactor containment vessels with integrated air injection, heaters, and sensors. All surrounding the central control stack encompassing filtration, control, pump, and valving systems required for full automation.

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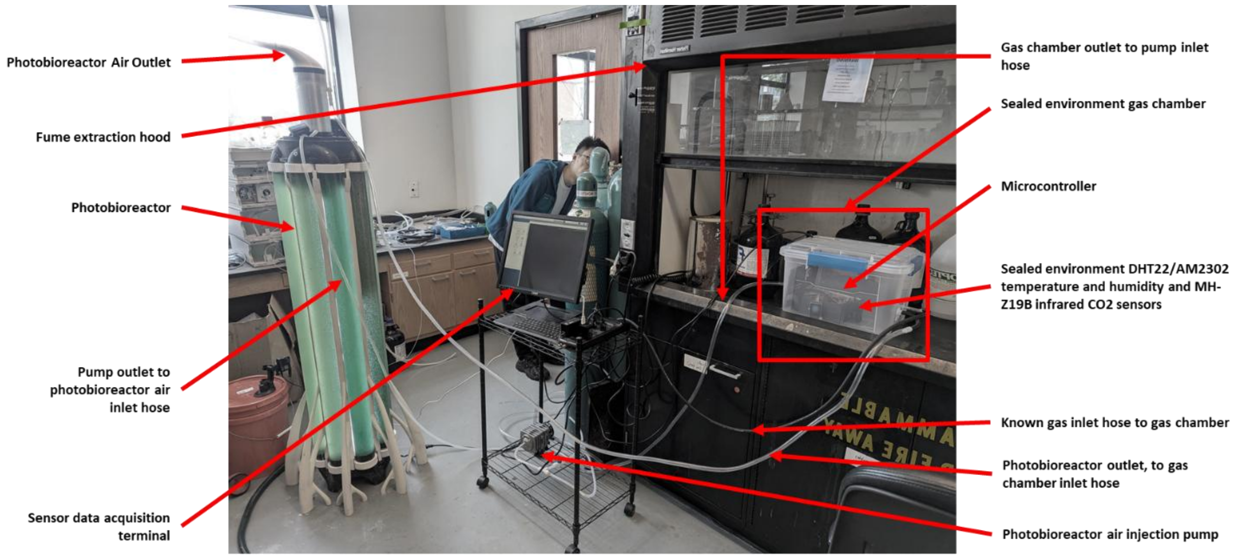

Figure 2: Sealed photobioreactor, gas chamber, sensor, and terminal system. System was modified overall to be a closed design with inlet and outlet pipes routing to a sealed chamber with internal sensor pack and gas injection ports for known gasses.

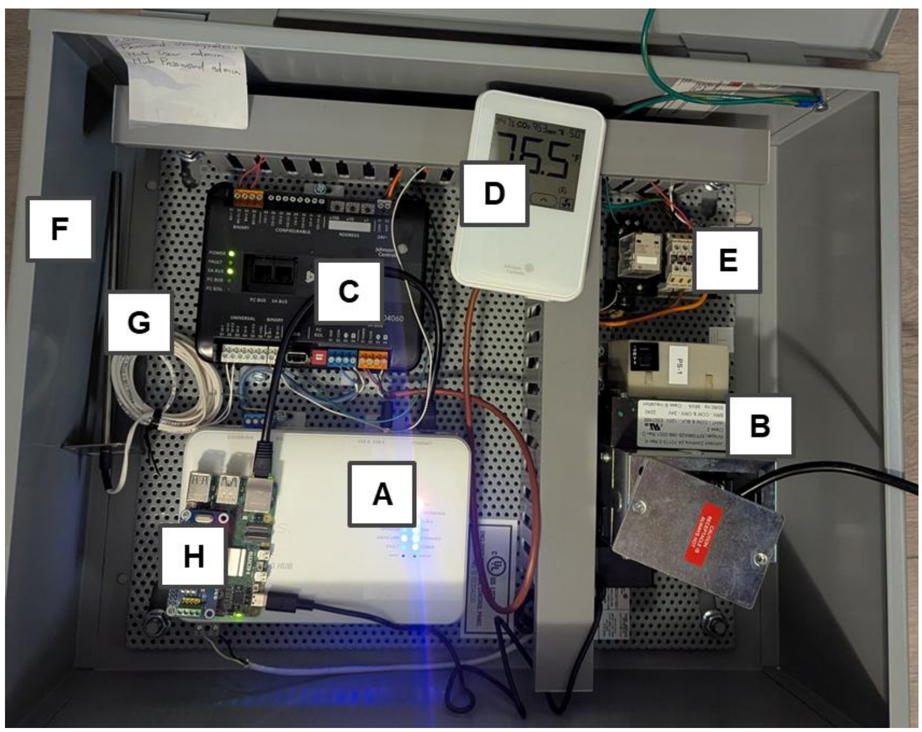

Figure 3: Simulated commercial HVAC system. [A] is the Verasys Smart Hub, a device that helps connect and network multiple HVAC devices. [B] the power supply. [C] is the Johnson Controls CGM field controller which is the device that directly controls equipment. [D] is a thermostat and CO2 sensor from a typical commercial application. [E] is a relay that simulates the outdoor air valve, or fresh air damper. [F] is the control panel box where the equipment is mounted. [G] provides system temperature data for the HVAC controller. [H] is the VerdeTerra BACnet IP control interface device that provides two-way communication with photobioreactor.

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3.2 Sensor Package

The system utilized a range of low-cost, embedded sensors to monitor environmental and performance parameters during testing:

- **CO_2:** MH-Z19B NDIR sensor
- **NO_2:** MQ-135 metal oxide sensor
- **CO:** MQ-7 electrochemical sensor
- **SO_2:** MQ-135 (dual-use for NO_2 and SO_2 detection)
- **Temperature & Humidity:** DHT22 (AM2302) digital sensor
- **Power Consumption:** Inline digital watt-hour meter

Figure 4: Data acquisition package and sensor array mounted inside closed system chamber for gas concentration monitoring during VOC reduction testing.

These sensors were positioned within the sealed environment chamber shown above in **(Figure 4).** Data was logged continuously using Raspberry Pi-based microcontroller and monitored live for setting initial concentrations and monitoring performance via a display screen mounted externally to the system shown above in **(Figure 4).** The sensor array has a small 5v 1in fan mounted to the side of the box to promote air mixing over the sensor package. With air being drawn in over the top opening for the sensor array and expelled out the side by the fan.

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3.3 Closed System Development

Initial attempts with inflatable paint chambers failed to meet leakage specifications. VerdeTerra pivoted to using the sealed bioreactor itself as a test volume. Final sealed tests showed <5% leakage over 6 hours. This time corresponded with the time interval of experimentation. The system by design is a sealed device to restrict water/foam leakage as well as create a controlled habitat for the microalgae. The modifications necessary to completely seal the photobioreactor include a custom filter top assembly that sealed the top gas exit from the photobioreactor and led instead to a tubing connection to a sealed gas chamber. The second modification was to disable internal air pumps, as they are designed to take in atmospheric air, and send internal photobioreactor air injection tubing directly to an external air pump with inlet routed to a sealed gas chamber and outlet to the sealed photobioreactor. The sealed gas chamber and photobioreactor internal air volume for the closed system is ~1m^3. This design also allowed the team to position the closed experimental chamber within an exhaust hood during experimentation to safely release VOC's after testing completion. The closed cycle system had an additional known gas injection port on the sealed gas chamber. The system overview can be seen above in **(Figure 2).**

3.4 Experimental Matrix Setup

Experimental testing of VOC reduction was performed at Georgia Institute of Technology working with Dr. Yongsheng Chen, Professor School of Civil and Environmental Engineering. Tests were conducted with known gases supplied by Airgas. The tests were performed in the following order:

1. CO_2 at 800ppm, 3000ppm, and 5000ppm for reduction performance over 6 hours.
2. NO_2 at 1000ppm and 500ppm for reduction performance over 6 hours.
3. SO_2 at 100ppm for reduction performance over 6 hours.
4. CO_2 reduction at 5000ppm (3x sequential tests for algae density effects).
5. CO at 100ppm, 50ppm, and 10ppm for reduction performance over 6 hours. (Delayed results, amendment to final report will be sent upon experimentation completion)
6. Energy consumption testing over 72 hours (performed at VerdeTerra facility)

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3.5 HVAC Integration Experimentation

A BACnet/IP-compatible test bench was constructed with popular off-the-shelf commercial HVAC components likely to be encountered in market. The system overview can be seen above in **(Figure 3).** The key system components are comprised of the following:

- Johnson Controls CGM controller
- Verasys Smart Hub
- Relay-driven air damper simulation
- Raspberry Pi running BACnet stack

VerdeTerra successfully demonstrated communication between the bioreactor and HVAC test system. Relay signals toggled simulated outdoor air valve based on a calculation of photobioreactor efficiency calculated by algae density, temperature, and CO_2 absorbency efficiency. To quickly simulate various changing conditions of a photobioreactor, a simulation of a bioreactor was developed to test the HVAC integration software's ability to cycle the outdoor air valve in reaction to the photobioreactor efficiency at the time. A status plot of the simulation running is shown below in **(Figure 5).**

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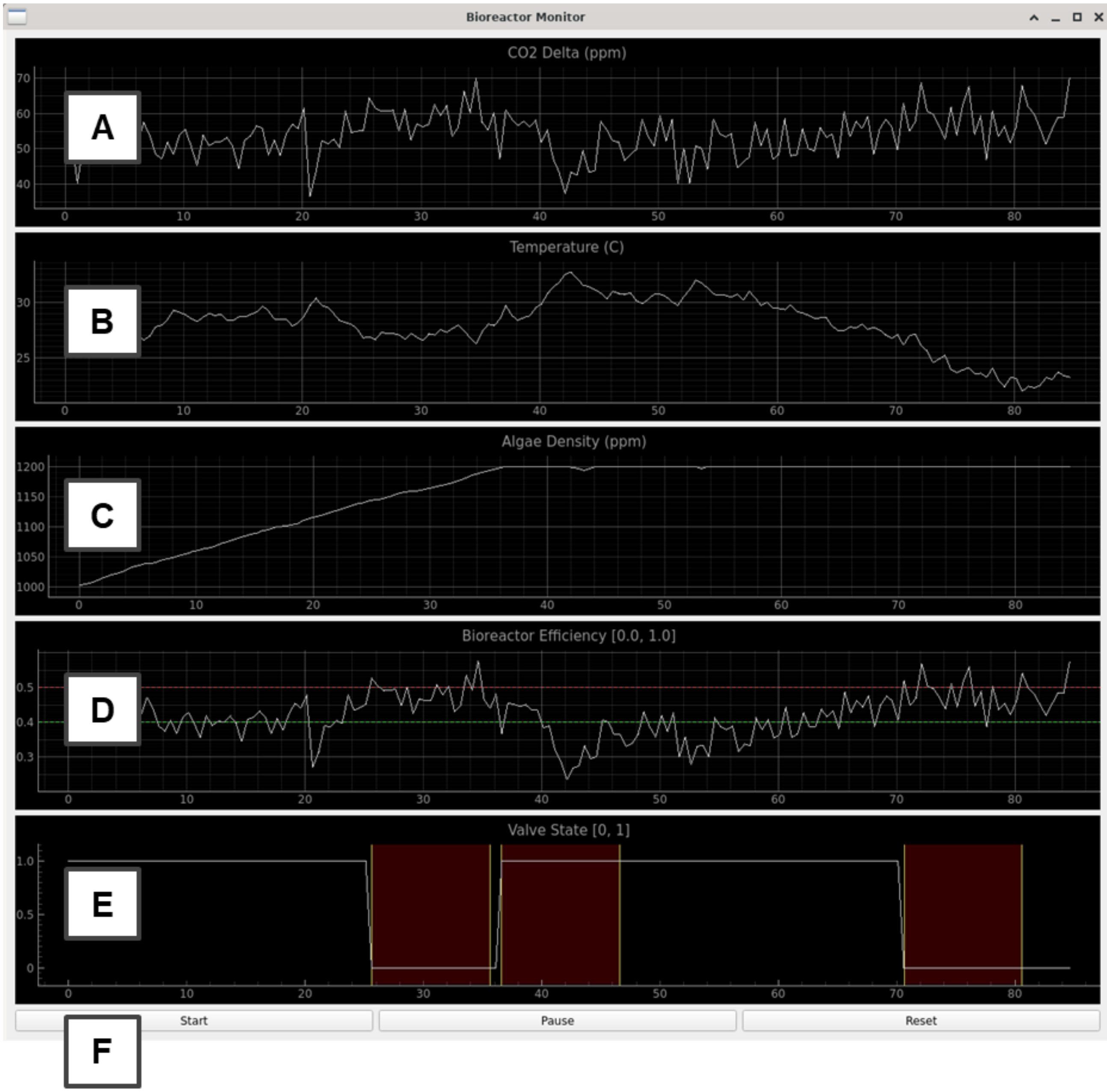

Figure 5: Simulated photobioreactor system with HVAC integrations status view of outdoor air valve actuation status. [A] shows the CO2 delta, or inlet – outlet, reading from the photobioreactor. Showing the CO2 absorption efficiency as an indicator of overall VOC reduction performance. [B] is a temperature reading from the photobioreactor algae culture. [C] Indicates simulated photobioreactor algae density. [D] Calculated photobioreactor efficiency to use as a HVAC outdoor air valve actuation condition. [E] HVAC outdoor air valve status (Open/Closed), with logic to prevent over-actuation and rapid changes in state, shown by red box, timeout period. [F] System simulation controls.

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4. Results and Discussion

4.1 Closed System Testing

During the development of the VOC reduction testing protocol, VerdeTerra initially attempted to use a commercially available inflatable painting chamber as a sealed test environment. Despite efforts to reinforce and seal numerous leakage points, the chamber's inherent design resulted in persistent and unmanageable air leaks. These limitations prevented reliable control of gas concentrations and rendered the setup unsuitable for valid experimentation. As a result, the team pivoted to a more effective solution by repurposing the photobioreactor itself as a closed system. Outfitted with gas injection and outlet ports, the photobioreactor served as a repeatable and controlled test chamber for VOC reduction testing.

For a closed testing validation test the system was filled with CO2 up to a level of 3500 ppm with the photobioreactor air injection off to prevent algae breakdown of the CO2. The CO2 concentration fluctuated within the range of 3100-3900 ppm for 23 hours and 39 minutes. This fluctuation may have been caused by pure CO2 pockets moving around the system, or CO2 settling and disturbance by the small sensor fan. However, the concentration fluctuations moved in both directions over the 23-hour 39-minute period showing a sealed system. This more than covered the 6-hour testing window of experimentation.

4.2 VOC Reduction Testing

All pollutant reduction experiments were conducted over a **6-hour testing window**, except in cases where concentration levels stabilized early or, in the case of SO_2, where algal viability rapidly declined.

For CO_2, at an initial concentration of 500 ppm, algae exhibited steady CO_2 uptake with moderate biomass growth, achieving a removal efficiency of approximately 60% as shown in **(Figure 6a).** When the CO_2 concentration was increased to 1000 ppm and subsequently to 3000 ppm, a significant enhancement in adsorption efficiency was observed, with a peak removal efficiency of 71% at 3000 ppm **(Figure 6b).** This improvement is attributed to the increased availability of CO_2 for photosynthesis, which also led to accelerated biomass accumulation. However, at a higher concentration of 5000 ppm **(Figure 6c),** the removal efficiency declined to approximately 45%. This reduction may be due to CO_2 oversaturation

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or pH imbalances within the culture medium, which can disrupt cellular metabolism and inhibit further uptake. Our additional experiments indicate that microalgae possess a measurable capacity to absorb nitrogen dioxide (NO_2). When the initial NO_2 concentration was 1000 ppm, levels decreased to approximately 800 ppm, indicating a 20% reduction as shown in **(Figure 6e)**. At a lower initial concentration of 500 ppm, the final concentration was around 370 ppm, reflecting a 26% removal efficiency as shown in Figure 5d. These results suggest that microalgae can adsorb NO_2 to a limited but quantifiable extent, likely through surface interactions or biochemical assimilation. In contrast, exposure to sulfur dioxide (SO_2) revealed significant toxicity to the microalgal culture as shown in **(Figure 6f)**. At a concentration of 100 ppm, the microalgae exhibited visible chlorosis (yellowing) within one hour of exposure, indicating severe physiological damage and loss of viability. Sensor package for measuring SO_2 was inaccurate at measuring in the 1-3 ppb range required and lower concentrations could be reliably achieved. Due to this acute toxicity, reliable SO_2 absorption data could not be obtained under these conditions.

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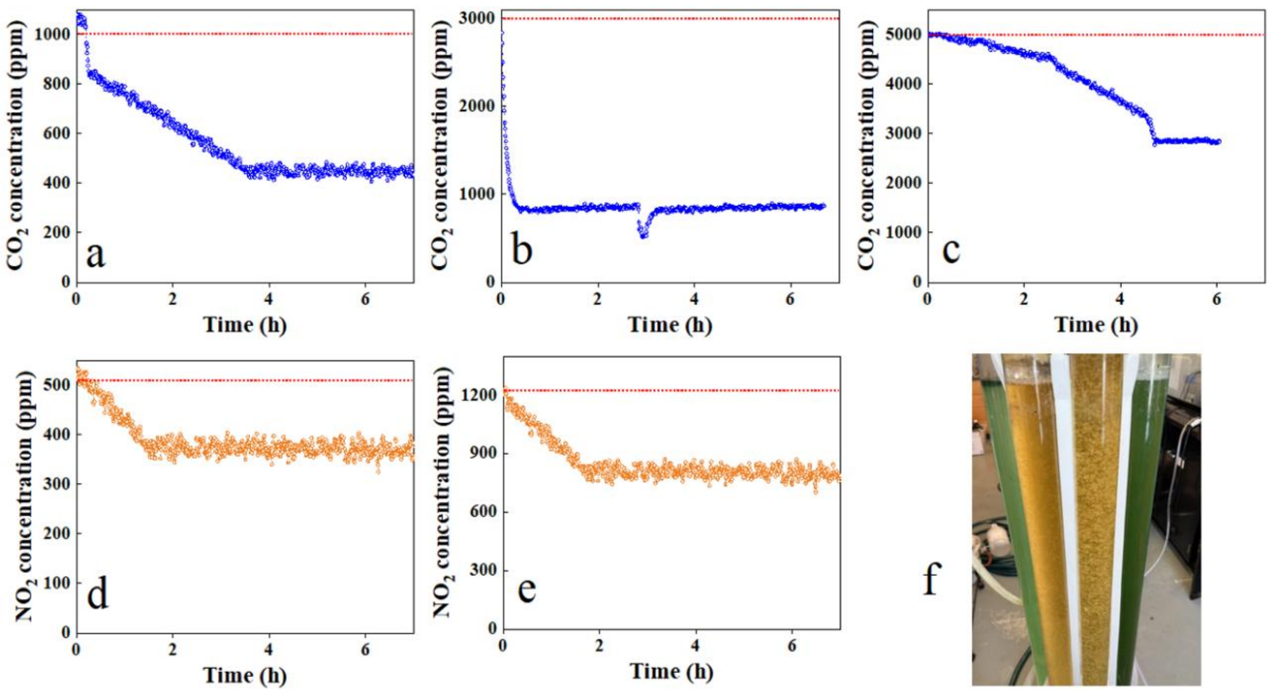

Figure 6 Adsorption efficiency of microalgae for CO_2, NO_2, and SO_2 at various concentrations with red line indicating initial concentration. (a, b, c) CO_2 removal efficiency at 1000 ppm, 3000 ppm and 5000 ppm. (d, e) NO_2 absorption efficiency at 1000 ppm and 500 ppm concentration. (f) Effect of SO_2 exposure on microalgae viability, with visible chlorosis observed at 100 ppm after 1 hour of exposure, preventing further SO_2 absorption measurements.

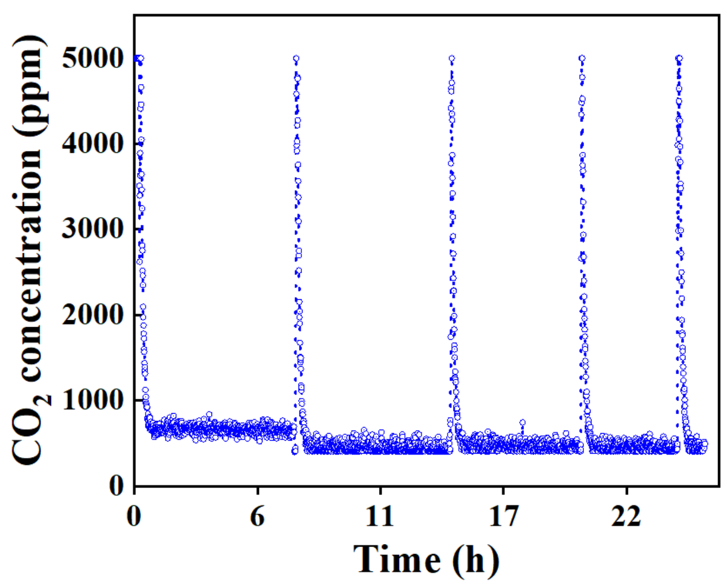

Figure 7. 5000 ppm CO_2 Reduction for density repetition testing.

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Continuous CO_2 reduction experiments were conducted with an initial concentration of 5000 ppm to assess the impact of algal density on removal efficiency over time. As shown in **(Figure 7)**, the CO_2 concentration rapidly decreased during successive tests, indicating effective removal. The data demonstrate that higher algal densities enhance CO_2 adsorption performance, as reflected by more pronounced reductions in CO_2 levels over time.

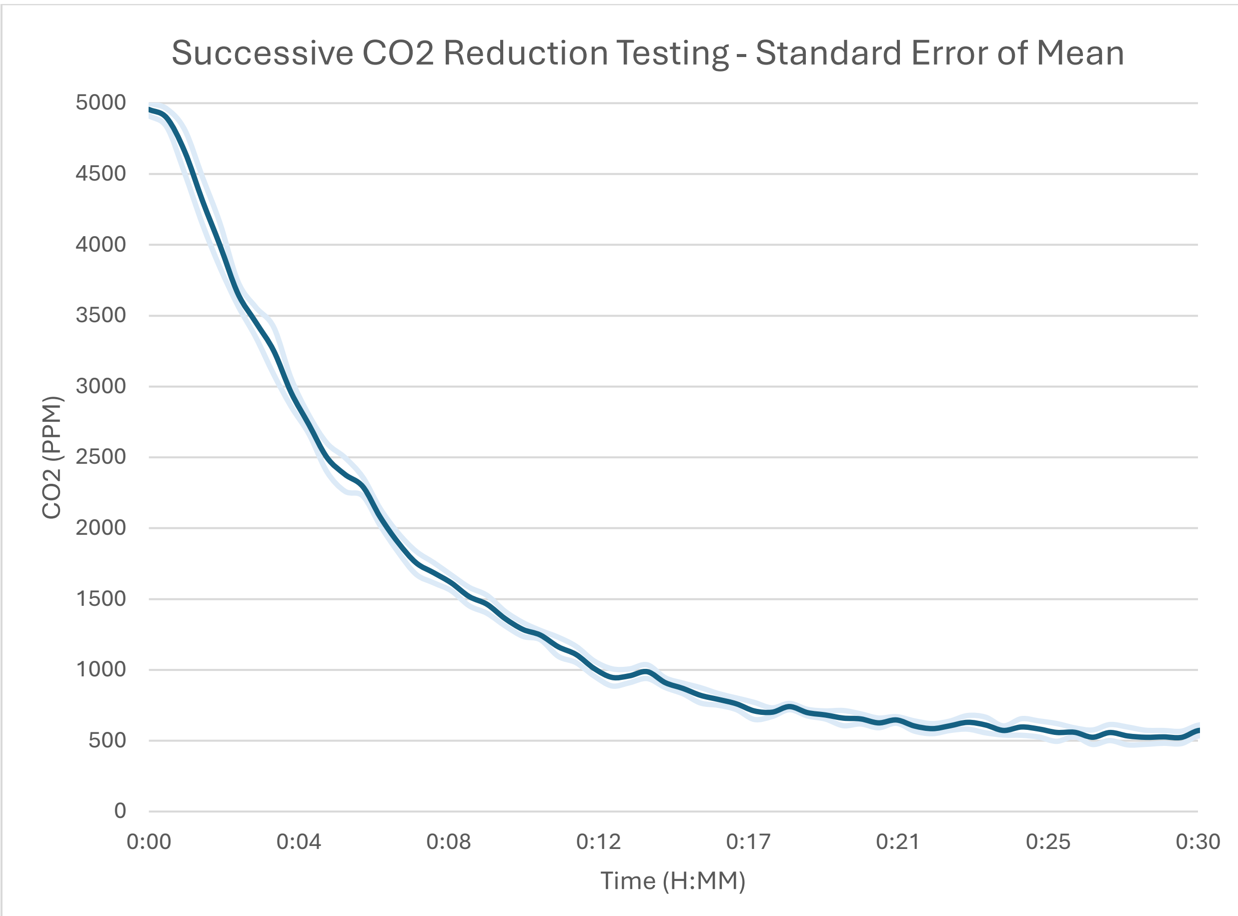

Figure 8 Standard error of the mean (SEM) for 5 successive CO2 absorption tests for the VerdeTerra photobioreactor sealed environment.

(Figure 8) demonstrates a consistent and rapid decrease in indoor CO_2 concentration across five repeated trials using VerdeTerra's photobioreactor system. Starting near 5000 ppm, CO_2 levels declined steadily to below 1000 ppm within approximately 15 minutes, with diminishing returns as equilibrium was approached. The shaded region around the mean line represents the standard error of the mean (SEM), indicating low variability between tests and high repeatability of the system's performance. These results affirm the

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system's capacity for reliable and sustained CO_2 scrubbing, validating its effectiveness for real-time pollutant reduction in sealed environments.

CO testing was delayed due to shipping delays from the certified gas supplier. Despite early ordering, the gas had not arrived at the conclusion of the performance period. All hardware and protocols are ready for execution, and CO experiments will be conducted immediately upon receipt. Results will be submitted as an amendment to this final report.

4.3 Power Consumption Testing

Power consumption testing was conducted to assess the energy requirements of the VerdeTerra photobioreactor during continuous operation in its highest power demand state. This state is defined by all subsystems, including the fluid circulation pump, lighting, controller, air bubbler, and heaters actively running.

The system drew a steady current of 0.930 amps, and energy usage was recorded at defined intervals using an inline watt-hour meter. The average power draw was calculated using the following formula:

$$Average\ Power\ (W) = (Energy\ (kWh) \times 1000)\ /\ Time\ (hours)$$

Results:

- **24.6 hours:**
  Energy consumed = 2.390 kWh
  $$Average\ Power = (2.390 \times 1000)\ /\ 24.6 \approx 97.2\ W$$
- **48 hours:**
  Energy consumed = 4.659 kWh
  $$Average\ Power = (4.659 \times 1000)\ /\ 48 \approx 97.1\ W$$
- **122 hours:**
  Energy consumed = 11.820 kWh
  $$Average\ Power = (11.82 \times 1000)\ /\ 122 \approx 96.9\ W$$

These consistent values demonstrate that the system maintains a stable energy footprint of approximately **97 watts** under full operation. A supplemental figure **(Appendix E1)** includes images of the power meter display at each of the recorded data points.

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4.4 HVAC Integrations Testing

The photobioreactor simulation also connected to a Message Queuing Telemetry Transport (MQTT) broker called Mosquitto, which acts as a central server to subscribe and publish messages and data. MQTT is a lightweight and open-source messaging protocol used for machine-to-machine (M2M) communication. Any MQTT broker can be used for this purpose, but Mosquitto was an open-source software we could run locally for testing. To communicate with commercial HVAC systems, the team utilized an industry standard protocol called the Building Automation and Control network (BACnet), a communication protocol designed for building automation and control systems. The team also developed a BACnet software controller which translated messages from MQTT to messages that could be sent over BACnet, allowing for reads and writes to BACnet devices and their respective objects.

The lightweight simulation served as a client which was able to send messages to many of the devices in **(Figure 3)**. For example, we could read and activate the relay shown (which would turn on an LED indicator), as well as fetch data from the thermostat or CO2 sensor. If the device has an endpoint defined and accessible through the Johnson controls CGM controller and Verasys smart building hub, the BACnet controller software we developed would map out those points to make them accessible over our MQTT messaging scheme. This allows for full integration with a HVAC equipment over BACnet/IP that is agnostic of the actual client performing the reads or writes.

To verify BACnet controller functionality, the Mosquitto MQTT client was employed using its pub and sub commands. First, a subscription to the centralized broker was initiated to listen for BACnet-related messages with the following command:

```
mosquitto_sub -h localhost -p 1883 -t 'bacnet/#' -v
```

Subsequently, a publish command was used to send a test signal to the controller:

```
mosquitto_pub -h localhost -t 'bacnet/binary-
output/2132/presentValue/set' -m ''
```

When executed, the subscription terminal displayed serialized JSON output reflecting the relay status within the test setup, for example:

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{"type":"boolean", "value":true}

This confirmed successful message transmission and control response through the MQTT-BACnet interface.

4.5 Albero Carrier Board for Sensor and Relay Integration

As a major steppingstone for streamlined production and integration with HVAC systems as described above, we also developed hardware for a carrier board to integrate our compute module with isolated relays and sensor connections all on one board. The board was designed to compress the various disparate electronics that must be sourced from off-the-shelf equipment into a single board that maintains software compatibility and increases capability for future HVAC integrations on commercial applications.

(Appendix B1-3) showcases the evolution of the schematic capture and PCB design. The focus was on maintaining signal integrity and ensuring that the board is developed to meet future certifications that are desired by consumers and business customers.

The board is fully compliant with the Raspberry Pi 5 standard that defines how the FPGA Mezzanine Card (FMC) connectors are laid out and routed, so that we can design or re-use prepared compute modules for the actual processing of sensor data and control of the relays.

5. Conclusions

The Phase I project conclusively demonstrated the feasibility of VerdeTerra's Spirulina-based photobioreactor as a scalable, HVAC-integrated indoor air purification solution. Through a combination of sealed system testing, pollutant reduction validation, HVAC integration, and power consumption measurements, the project achieved all major technical milestones and delivered a robust foundation for Phase II development.

Key Experimental Outcomes:

- **CO_2 Reduction Performance:** Across five successive tests at an initial CO_2 concentration of 5000 ppm, the photobioreactor consistently reduced CO_2 levels to below 1000 ppm within approximately 15 minutes. The average CO_2 reduction

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efficiency at 3000 ppm reached **71%**, while 500 ppm and 1000 ppm tests showed efficiencies of **60%** and **68%**, respectively. At 5000 ppm, efficiency decreased slightly to **~45%**, likely due to oversaturation or pH limitations.

- **Repeatability and Statistical Confidence:** The system demonstrated excellent consistency, with the standard error of the mean (SEM) remaining low across all five trials (Figure 7), indicating high experimental repeatability and control.
- **NO_2 Absorption:** Tests at 500 ppm and 1000 ppm resulted in reductions to **370 ppm** and **800 ppm**, corresponding to **26%** and **20%** removal efficiencies. These values affirm the system's capacity to adsorb nitrogen oxides at measurable rates.
- **SO_2 Toxicity:** At 100 ppm, microalgae exhibited visible chlorosis within one hour, halting further uptake. While SO_2 absorption data was not obtained due to acute toxicity, the findings inform future strain selection and operational safeguards.
- **Closed System Integrity:** A static CO_2 test held at 3500 ppm without algae circulation showed minimal fluctuation (3100–3900 ppm) over **23 hours and 39 minutes**, confirming system leak rates below **5%**—well within the target range for 6-hour test windows.
- **Power Consumption:** Continuous power draw remained stable across all durations, averaging **~97.1 W**. Specifically, energy consumption was recorded as:
    - **2.390 kWh** over 24.6 hours
    - **4.659 kWh** over 48 hours
    - **11.820 kWh** over 122 hours
- **HVAC Integration:** A BACnet/IP-compatible control module demonstrated real-time communication with a simulated HVAC system, successfully toggling a relay-actuated air damper based on photobioreactor CO_2 absorption performance. MQTT-BACnet messaging was verified using serialized JSON outputs in real-time system simulations.

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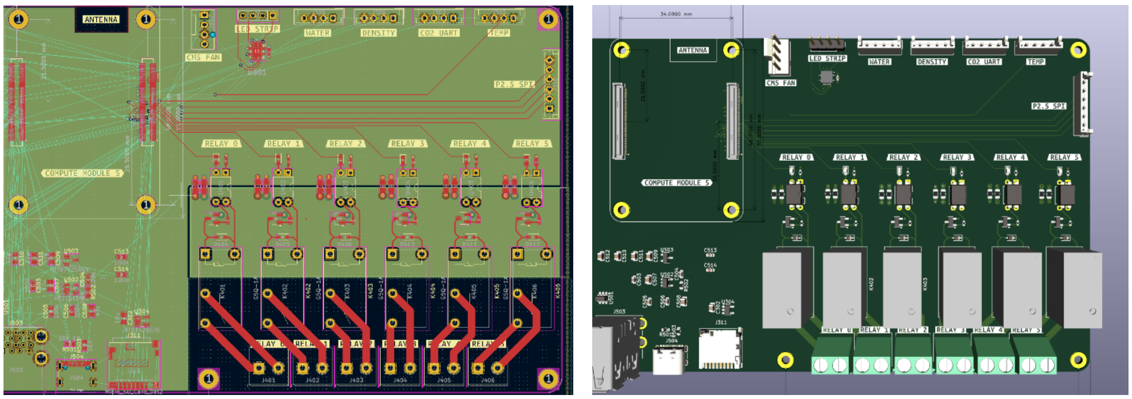
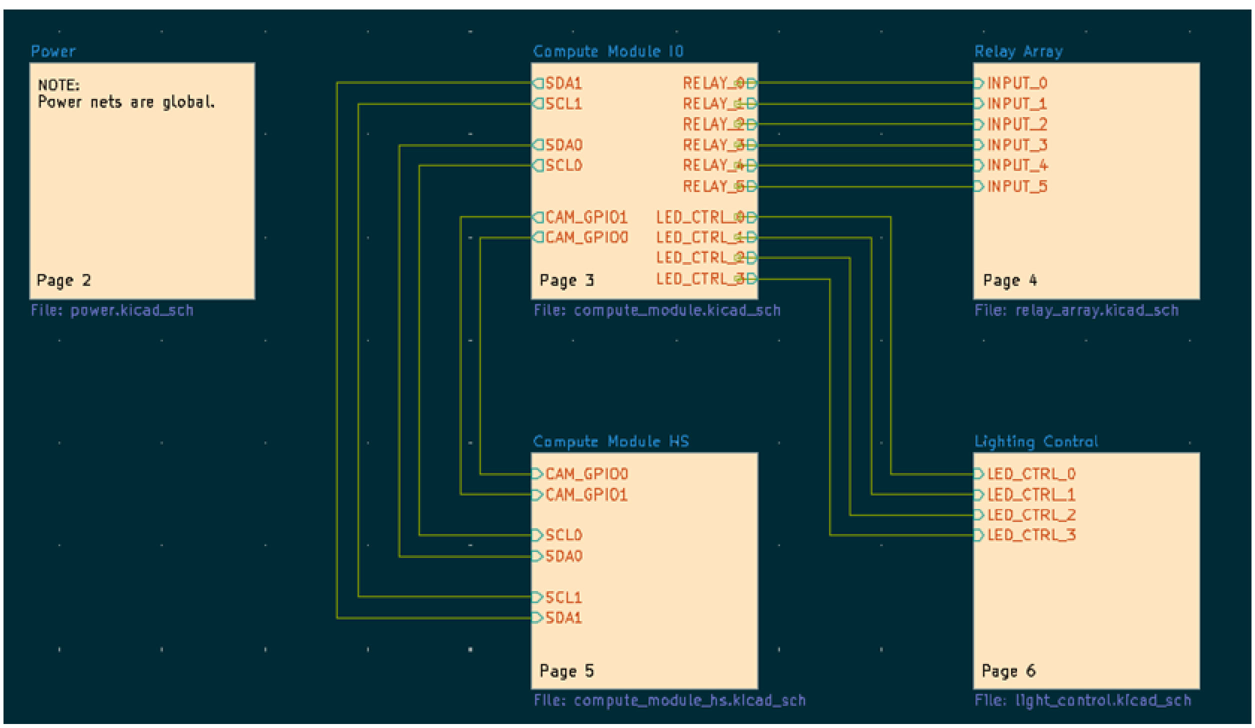
Appendices

- A. Monthly Progress Reports (M1–M5)
    - Note: All monthly progress reports (Months 1–5) were submitted to the EPA via the required reporting system and are not included here to avoid duplication.
- B. PCB Design Schematics



Appendix B1: HVAC integrations control board layout schematics for photobioreactor. Enabling communications between systems.



Appendix B2: Carrier board system diagram used in the schematic capture.

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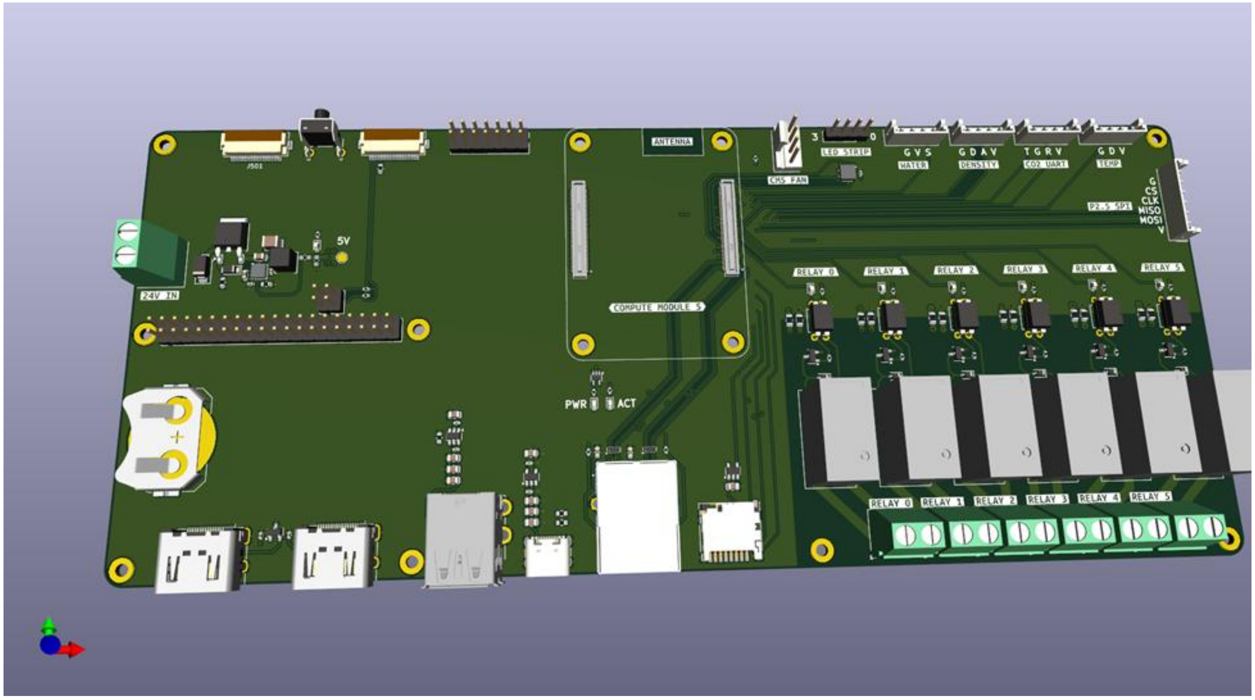
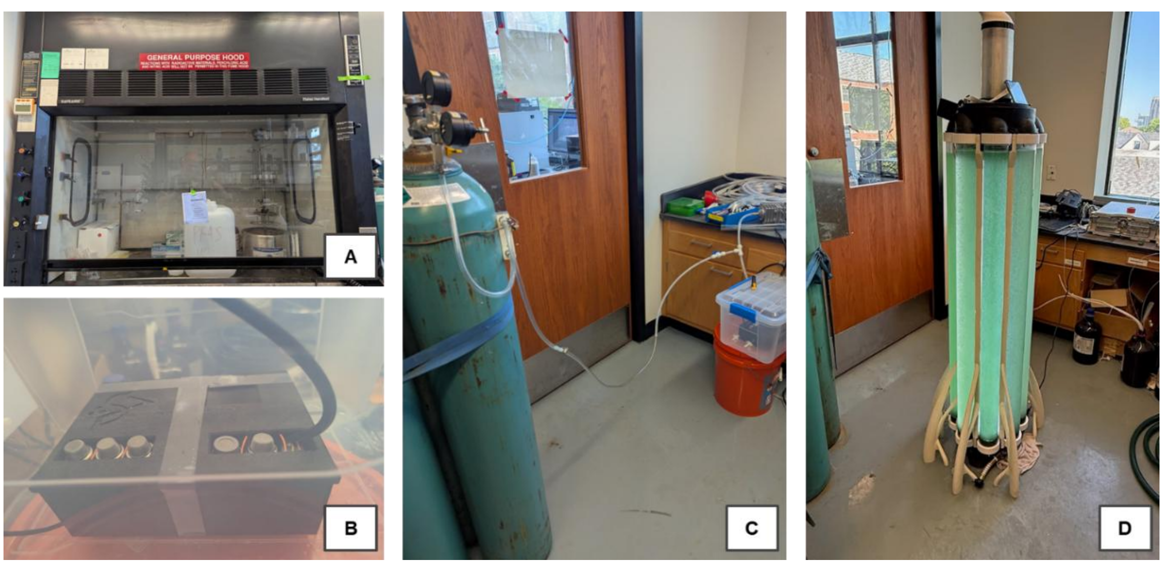


Appendix B3: Carrier board finalized 3D PCB render.

- C. Testing Photos



Appendix C1: Photobioreactor setup. A is the exhaust gas hood to vent experimental gasses safely. B is the closed system test box with sensor and data acquisition device. C is the known gas canisters and hosing to feed sealed system. D is the photobioreactor with algae culture.

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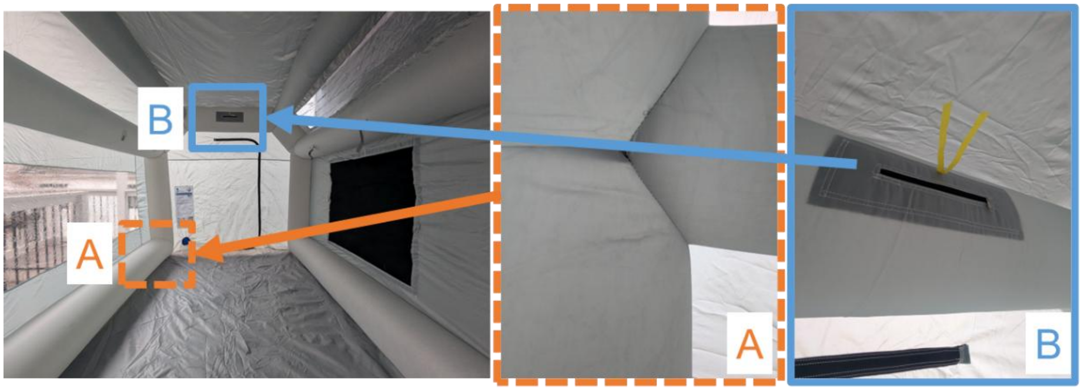
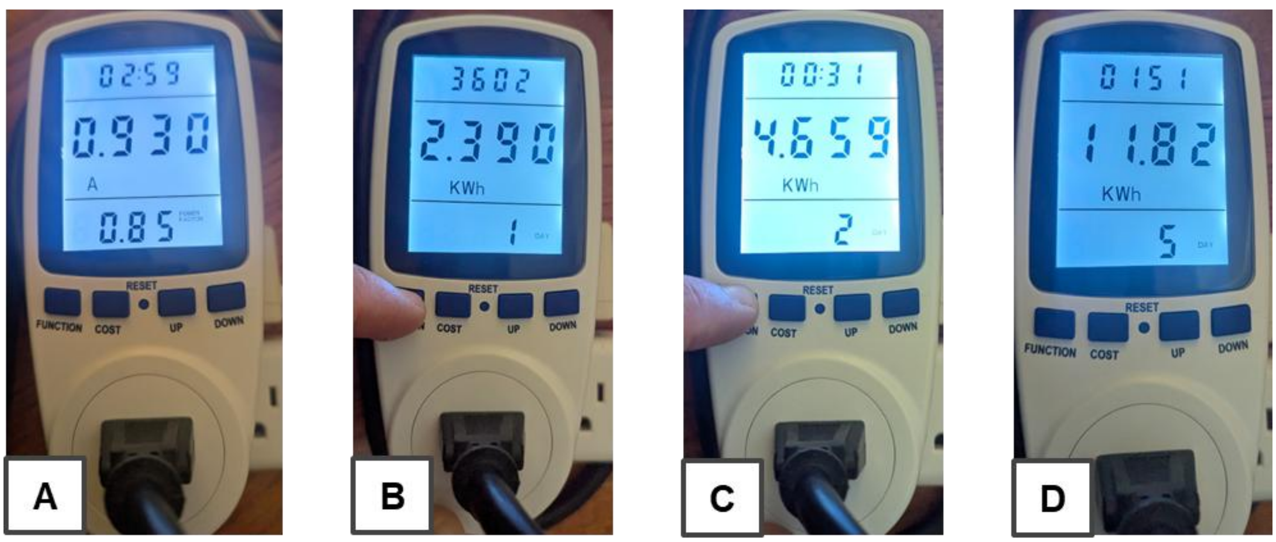


Appendix C2: Commercial painting chamber during closed environment testing. Highlighting larger air leakage areas that were unable to be sealed effectively to conduct reliable experimentation. This first option required a complete closed system rethinking of experimental design.

- D. Experimental Data Charts [To be added]



Appendix D1: Power consumption testing with watt meter on photobioreactor system at peak load conditions. [A] shows an amperage draw. [B] the kWh usage over 24 hours and 36 minutes. [C] shows the usage in kWh for 48 hours. [D] shows the 121 hour and 51-minute usage in kWh.

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