UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Micro-Brewery Symbiosis with IOT-Enabled Controlled Environment Agriculture

by Solomon Ould

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Associate Professor Nick Bennett

University of Technology Sydney
Faculty of Engineering and Information Technology

September 2024

Certificate of Original Authorship

I, **Solomon Ould**, declare that this thesis is submitted in fulfilment of the requirements for the award of **Doctor of Philosphy**, in the **Faculty of Engineering and IT** at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Date: 24/09/2024

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Abstract

To address the twin challenges of urban food security related to climate change and increasing microbrewery popularity leading to further CO_2 emissions [1] this study designed, built, and operated a fully sealed, IoT-controlled vertical hydroponic farm (440-plant capacity) co-located inside a working brewery in Sydney, Australia. Over twelve months the enclosure was operated with various experiments performed to test the viability of different aspects of the system.

A prototype low-pressure harvester diverted raw fermentation gas directly into the grow chamber for CO_2 enrichment. Continuous monitoring showed plant demand could depress internal CO_2 to 133 ppm by late afternoon (with external air exchange disabled), drawing down roughly 100 ppm day^{-1}. Direct injection restored levels to 900-1500 ppm for these experiments. Gas Chromatography confirmed a CO_2 purity of 99.975%. Calculations were performed to determine the resulting rise in total volatile hydrocarbons for enriching the chamber from 400 ppm to 1500 ppm, showing a worst-case estimate of 2.7 ppm – well below occupational hazardous exposure limits.

Growth trials with four substrates demonstrated that pure Grow Wool delivered the highest performance, yielding a mean fresh mass of 109.8g per lettuce—57 % heavier than clay balls (70.2 g) and 40 % heavier than vermiculite (78.2 g). At 82% planting capacity

the first 30-day cycle produced 9.11 kg of high-quality biomass from 83 Grow Wool based pods.

Although further development is needed to enhance control and reliability for robust, commercially scalable deployment, directly harvesting raw brewery fermentation CO_2 would provide clear advantages such as (i) reducing breweries' environmental footprint by capturing CO_2 otherwise released to the atmosphere; (ii) lowering growers' input costs by removing the need for bottled CO_2; (iii) supporting a circular-economy by repurposing on-site brewery CO_2; and facilitating urban agriculture through a local, co-located source of CO_2.

This work outlines a potential framework for safely capturing, metering, and injecting raw brewery fermentation CO_2 into controlled-environment agriculture, providing a foundation for future systems to expand upon.

Acknowledgements

I would like to express my gratitude to my PhD supervisor, Dr. Nick Bennett, for his guidance, patience, and unwavering support throughout this journey. His expertise and insight have been crucial in the realisation of my work, and I am deeply thankful for the opportunity to learn from and work with him.

A special thank you goes to my loving wife, whose support, understanding, and encouragement has been my foundation during the challenging moments of this PhD journey. Her love has been a constant source of strength and motivation.

To my beautiful daughter Emilia, despite being only one year old I can already see your fascinated and inquisitive nature, I am sure you will be brilliant at whatever you apply yourself to. You remind me daily of the wonders and simplicity of life outside of work, you mean the world to me.

I am deeply indebted to my father for his generous financial support and unwavering belief in my abilities. His sacrifices have not only made this endeavour possible but have motivated me to persevere and complete this journey.

I also wish to extend my heartfelt appreciation to the fellow PhD students in my cohort. Thank you for insightful discussion, brainstorming, and collaboration on many projects.

Finally, I want to thank Hawke's Brewing Company for generously supporting this project and allowing us both the space to conduct this research and access to their brewery and equipment.

Contents

List of Figures

List of Tables

Acronyms & Abbreviations

IOT	Internet of Things
CEA	Controlled Environment Agriculture
CAM	Centre for Advanced Manufacturing
UTS	University of Technology, Sydney
COTS	Commercial Off The Shelf
TVHC	Total Volatile Hydrocarbon Contamination
PPM	Parts Per Million
VOC	Volatile Organic Compound
HVAC	Heating Ventilation and Air Conditioning
MQTT	Message Queuing Telemetry Transport
MCU	Micro Controller Unit
RH	Relative Humidity
PAR	Photo-Synthetically Active Radiation
PPFD	Photosynthetic Photon Flux Density

Chapter 1

Introduction

In our current geo-political climate with steady population growth and rapidly depleting arable land and conditions, innovative solutions to food production are becoming increasingly important. Among potential future food production solutions, vertical hydroponic farming solves a number of contemporary food production and sustainable agriculture issues [3], while introducing some new problems of its own. As detailed by Despommier [4], this method of modern agriculture fosters the cultivation of crops in vertically stacked layers within controlled indoor environments. It relies on nutrient-rich water solutions and inert stabilisation medium instead of traditional soil. The benefits encompass increased yield per square meter, substantial water savings, and the ability to grow crops year-round and in any climactic conditions [4].

However, the potential benefits of vertical hydroponics are expanded when coupled with modern Internet of Things (IOT) technology [5–7]. IOT devices form a comprehensive network of interconnected sensors and controllers which help to facilitate real-time monitoring and automation of diverse environments. When applied to vertical hydroponics, IOT's contribution streamlines operations and reduces the human labour required to ensure optimal plant growth conditions. The automation processes can effectively monitor humidity, light intensity, and nutrient levels, among many other parameters, eliminating the requirements for constant manual checking and adjustments traditionally required.

The amalgamation of IOT with agriculture offers a glimpse into a potential future where urban areas seamlessly coexists with commercial food production.

Farming, by its nature, involves a plethora of recurring tasks, such as watering, fertilising, monitoring environmental conditions, and more. With the integration of IOT sensors and automated systems, many of these tasks can be self-regulated, not only ensuring precision but also freeing up human resources for more strategic roles, such as system optimization, research, and development. Ray et al.[8] explored the use of different IOT architectures to reveal how these systems, while vast, can be tailored to the unique requirements of various sectors. If the growing conditions for farming can be appropriately monitored using smart low cost sensor arrays there is a clear path towards urban farming with an array of benefits for society in both quality and reliability of food production. A synthesis of these elements promises enhanced yield and sustainability but also a less labour intensive approach to farming, where machines primarily control the growth of plants and there is less requirement for land clearing to build farms [9, 10].

The use of CO_2 supplementation is commonplace in the hydroponics industry due to the high concentration of plants inside a small area, coupled with the expense of heating or cooling the internal atmosphere, which requires minimal ventilation to be energy efficient [11, 12]. A compelling opportunity arises from the CO_2 produced by breweries. Breweries, particularly during the fermentation process, but also during bottling, transport, and purging, generate significant amounts of CO_2 as a byproduct [13, 14]. While large-scale breweries often capture and reuse this CO_2, smaller breweries frequently release it into the atmosphere as waste. At the same time, indoor hydroponic growers often rely on bottled CO_2 to optimise plant growth in controlled environments where CO_2 concentrations directly influence yield and operational costs. This presents an untapped potential for symbiosis: smaller breweries produce CO_2 as waste, while indoor hydroponic growers require a CO_2 source.

This thesis will be the first to explore the integration of brewery-produced CO_2 with vertical hydroponic systems in an industrial symbiosis, monitored and controlled through IOT technology. The study focuses on engineering a smart, IOT-driven system that directs CO_2 from small to medium-scale breweries fermenters and redirects it to an adjacent indoor

hydroponic environment. The system is designed using cost-effective commercial off-the-shelf (COTS) sensors and open-source software, making it accessible for both academic researchers and potential future commercial applications.

The focus is on the engineering challenges associated with implementing this novel concept. We present the outcomes gleaned from our growth testing experiments, data analysis, and initial CO_2 introduction testing. These insights have been made possible through the implementation of the advanced data capture infrastructure described throughout.

The conceptual framework of the hydroponics enclosure is introduced alongside the contextual background of the research site. Subsequently, a review of current literature on modern hydroponic IOT-based systems is conducted to examine the state of the art. Also covered is relevant biology which affects any engineering decisions, and CO_2 capture methods currently used in brewing. Following this, the design of a novel hydroponic system is outlined, detailing the control systems, lighting, construction, and IOT-based automation framework. The results from system commissioning, including performance data and optimisation opportunities, are then presented. Following this, the process of CO_2 harvesting from an operational brewery is examined, exploring both the technical challenges and future possibilities for integrating this with vertical farming systems. The discussion concludes with an analysis of the implications of this work for future urban agricultural practices and the remaining challenges necessary for commercial implementation.

FIGURE 1.1: Hydroponics enclosure photograph. Photograph by the author (2024).

1.1 System Concept

The evolution of hydroponics towards a more automated system aligns with the broader trend in society of precision agriculture and sustainable food production. It is hoped that through leveraging IOT technologies and robotics, hydroponic systems can achieve higher levels of efficiency, productivity, and resource management [15]. Automation, remote monitoring, and data-driven decision-making are increasingly being integrated into agricultural systems, reflecting a broader trend toward more efficient crop management and resource use. One of several significant benefits of CEA is its water efficiency, and we aimed to implement as much water recycling as possible into the system.

This experiment aimed to fine-tune all growth-related parameters within the hydroponic system, driven by an inherent desire for optimisation. As the project progressed, it became evident that, from a systems engineering perspective, hydroponics involves grappling with

a web of complex, interrelated variables, each with its own unique set of implications. The interconnected nature of growing biological entities can often cause unintended consequences and reveals a landscape fraught with unanticipated outcomes. We endeavour to provide insight into some of these learning's through providing our design concepts, as built specifications, and results from over 12 months of testing. These pursuits have led us through a labyrinth of various design concepts, each bearing its own share of successes and setbacks, which we examine in this paper.

In addition to the optimisation of traditional hydroponic variables, the novel system described introduces the concept of CO_2 recycling within the design, sourced directly from waste CO_2 produced during the brewing process. Breweries, especially smaller-scale operations, often vent CO_2 produced during fermentation into the atmosphere as a waste product. Meanwhile, indoor hydroponic systems typically use bottled CO_2 to enhance plant growth. In a novel symbiotic relationship that aligns the needs of breweries with those of urban hydroponic farms the system is able to digest this waste CO_2 directly. This not only provides an environmentally sustainable method of CO_2 recycling but also highlights a new avenue for urban agriculture, where the integration of brewery CO_2 into hydroponic systems represents a sustainable solution to resource waste and agricultural productivity.

Chapter 2

Literature Review

This chapter offers an in-depth review of the literature on integrating IoT technology in hydroponic systems, with particular attention to recent advancements and key design principles. It explores studies that highlight how IoT can optimise environmental controls, and automate processes in hydroponic environments. The review also considers critical challenges, such as sensor accuracy, scalability, and long-term operational viability—and shows how addressing these issues is essential for achieving the research goals of building a brewery-integrated hydroponic system. By synthesising prior work, this chapter establishes a clear foundation which is directly aligned with the design choices and experimental focus of this project.

Building on this foundation, the following section examines the state of the art in hydroponics, reviewing existing systems, their demonstrated capabilities, and key recommendations for future designs. These insights are framed in terms of their relevance to the research questions posed in this thesis.

2.1 State of the Art in Hydroponics

Ingole et al. (2024) reviewed existing systems and identified the the need for further research into optimising IOT sensors for specific crop types and environmental conditions. Their study focused on integrating IOT technology into hydroponic systems to enhance

the monitoring and irrigation process. Their research demonstrated that real-time monitoring of environmental parameters through IOT significantly improves sustainability and productivity in hydroponic agriculture by providing precise control over factors crucial for plant growth [16].

Sayankar et al. (2024) introduced IOT, and solar power to optimise plant growth conditions. By using sensors to monitor environmental parameters their system enables farmers to manage hydroponic farms via a mobile application. This integration enhanced resource efficiency and supported data-driven crop management in commercial hydroponic setups. They highlighted the need for developing more cost-effective and energy-efficient IOT solutions. [17]

Attempting to advance Nutrient Film Technique (NFT) hydroponics with smart automation's, Ghate and Malpe [18] focused on using IOT technology to automate NFT hydroponics. Their study addressed urban farming challenges by automating the monitoring of key parameters, thereby reducing the need for manual intervention. They recommended that future work should aim to develop more sophisticated control algorithms that can dynamically adjust nutrient and environmental parameters based on real-time data.

Rahmat and Wibowo (2023), developed a smart grid concept integrating aquaculture with hydroponics using IOT and solar energy. Their system provided a sustainable solution for urban farming, enabling remote monitoring and control through IOT-based systems, trying to limit the challenges of land availability in urban areas. Their research was focused on focused on optimising power consumption, and they suggested developing systems that can autonomously switch between energy sources to maintain operations.

Khare and Khare [19] presented a solar-powered hydroponic system combining AI and IOT technologies to regulate critical factors such as pH and nutrient levels. Their work highlighted the benefits of using a mobile app for managing these parameters, in order to enhance the efficiency of hydroponic farming practices. They recommended that future research should explore integrating AI with IOT further to develop predictive analytics tools that can provide actionable recommendations for farmers.

A conference paper from 2023 described a hydroponic system using IOT for cloud-based monitoring and data analysis. It facilitated real-time telemetry and automated environmental control. The system allowed for sub-second streaming of data from the ground units to cloud servers, offering a comprehensive overview of plant health. The study revealed there is a gap in understanding the long-term effects of IOT-driven hydroponics [20].

Ramsari and Hidayat [21] employed IOT and micro controllers to automate plant nutrition management in hydroponics. Their system maintained optimal growth conditions by automatically adjusting nutrient levels from sensor data, with all information stored in cloud systems for later analysis. They suggested further research into improving sensor accuracy and developing more comprehensive algorithms for nutrient management tailored to specific plant requirements.

Using a Node MCU Interface, Manohar et al. [22] explored the application of Node MCU in automating hydroponic systems. They again highlighted the benefits of cloud-based data storage for enhanced monitoring and control. They recommended future studies investigate the potential of using wireless communication technologies.

Harikrishna et al. [23] explored the integration of IOT technology into greenhouse systems for hydroponics, utilising cloud-connected sensors to manage environmental parameters, a common feature in similar systems. They highlighted a significant gap in achieving seamless integration of IOT with other smart technologies.

Automation and control systems have become staples in modern hydroponics, serving to maintain optimal conditions by monitoring and adjusting nutrient levels, pH, temperature, dissolved oxygen, water flow rate, and water levels. Recent research has extensively examined the intersection of IOT technology with hydroponic cultivation, mostly focusing on addressing various control parameters [24–30].

The studies reviewed mostly yielded only proof-of-concept results, which is understandable considering the costs associated with prolonged testing. However, this limitation poses challenges:

Data and Accuracy: Collecting comprehensive datasets over extended periods is both resource-intensive and difficult, shorter studies raises questions about the efficacy of the methods when applied to commercial scale systems.

Scalability and Generalizability: Research conducted with limited samples may not be applicable to larger systems or different contexts. There is a clear need for more robust evidence supporting the scalability of these systems to larger farming operations.

There is a notable scarcity of extensive plant growth datasets publicly available for comparative analysis. More research is necessary to explore the capabilities of hydroponic systems with open control algorithms across various applications to address the broader challenges.

2.2 Design Principles

From a comprehensive analysis of prior literature the following were identified as design considerations, or potential gaps in current systems, and were used to guide development.

- Incorporate intuitive interfaces and mobile control to interpret IOT data and perform actions.
- Allow for advanced data analytics and enable real time algorithmic control from any sensor.
- Attempt to minimise cost of system where possible to allow for broader use.
- Allow for scalability and easy replication of control systems for iterative improvement.
- Provide better integration of all system components to form a single platform for development.
- Employ modularity to enable the reuse of code in other systems or areas.
- Develop open control algorithms for dynamic adjustment of environmental parameters.

- Focus design on urban integration and space efficiency.
- Improve accuracy of variables by using multiple sensors or algorithmic shaping.
- Allow for easier integration with other IOT devices and incorporate a range of technologies.
- Provide longer term insights and larger scale testing.

The hydroponic systems developed in the literature reviewed were primarily of a lab size or scale. Typically containing a relatively small amount of plants (5-30), in order to evaluate the scalability of these designs the proposed system was scaled to a medium size commercial setup containing 440 plants. This allows the data generated and insights reached to be more applicable to commercialisation of this technology on a larger scale.

2.3 Parameters Of Interest

A hydroponics system encompasses a multitude of potential variables, with each variable's importance being interconnected with external factors such as water quality and the chosen plant species. Due to the extensive range of possible optimisations within a single system, the scope of investigation was narrowed to elements that biological research has identified as most significant. "Plant Physiology, 5th edition" by Taiz and Zei [31] is a comprehensive reference that provides a wealth of biology-specific insights. While the literature contains substantial debate over the relative importance of certain parameters, particularly at the species level, there is a general consensus that the following variables are critically important for any plant species and were chosen as key parameters to automate:

1. **Light**: Fundamental for photosynthesis, light facilitates the conversion of energy into chemical energy. It also modulates processes such as phototropism, flowering, and seed germination [32]. To cater to these needs, a hydroponics system should control lighting and allow adjustment of both brightness and colour spectrum. This permits control over light intensity but also allows adjustment of specific wavelengths, emulating the variable spectrum of sunlight is an important factor for growth.

2. **Temperature**: The ambient air temperature is a primary determinant of plant metabolic rate. Temperature modulates the kinetics of photosynthesis, respiration, and numerous enzymatic reactions [33]. To ensure optimal temperature ranges, air conditioning must be provided that allows both heating in colder conditions, and cooling during hotter periods.

3. **Water**: Integral to plant cellular structure and physiology, water is indispensable for photosynthesis, nutrient absorption, and transpiration [31]. Hydroponic systems should guarantee a consistent and clean water supply, ideally by incorporating a filtered and automatically metered rain water supply, as well as a mains water backup and condensation recycling.

4. **Air and Carbon Dioxide (CO_2)**: CO_2 serves as a substrate in photosynthesis, and its concentration is essential for plant growth optimisation [34]. Monitoring of CO_2 concentrations should be applied, and supplementary CO_2 introduced to maintain the level inside the chosen crops ideal range.

5. **Nutrients and Soil Quality**: A spectrum of macro and micro nutrients are essential for plant growth, and their bio-availability is contingent upon other factors such as pH, and microbial interactions [35]. Hydroponic systems must employ a chemical dosing methodology and EC monitoring to constantly ensure the nutrient solution remains at optimal levels.

6. **pH Level**: pH modulates the solubility and bio-availability of minerals in the soil, thereby affecting nutrient assimilation [36]. To maintain pH within the optimal range, a chemical dosing system is required and pH probe located in the main nutrient reservoir to monitor the parameter. Automated readings should be verified through scheduled manual readings to confirm accuracy.

7. **Humidity**: Regulating transpiration rates, humidity levels can affect nutrient uptake and overall plant water relations [37]. Potential humidity-related issues can be avoided by using a dedicated dehumidifier, ideally this can be remotely activated based on temperature and humidity sensors.

In addition to addressing the above listed general parameters the specific hydroponics substrate and the chosen species of plant must be carefully considered.

2.4 Hydroponic Substrates

There are various types of hydroponic substrates. Substrates provide physical support for plant roots, providing a platform for the roots to grow and giving them mechanical support [38]. They are also responsible for retaining water and nutrients, making them available to the plant roots. The retention capacity is important for the consistent supply of nutrients, ensuring that the plants receive the necessary elements for growth and buffering the flow of the nutrient solution [38].

Lighter substrates promote proper aeration around the roots, which is important for preventing root rot. Substrates such as clay pebbles and Perlite are noted for providing better aeration due to their porous nature [38].

Substrates can also influence the pH of the nutrient solution depending on their composition, however inert substrates such as Grow Wool do not, which is an advantage [39].

Certain substrates can help prevent diseases by offering an inhospitable environment for pathogens. For example, sterile substrates like Perlite and Grow Wool reduce the risk of soil-borne diseases, which can be common in traditional soil-based agriculture [38].

The following hydroponic substrate types were considered for potential use in the enclosure based on suitability and local availability:

- Grow Wool:
  - Widely used and common due to its water retention and aeration properties, but it can have high environmental impacts due to its manufacturing process [38].
- Clay Balls:
  - Reusable and provide excellent aeration due to larger voids between pellets.

- Perlite:
  - Lightweight and provides good aeration and drainage, often mixed with other substrates to improve water retention [38].
- Coconut Coir:
  - A natural and sustainable product that retains water well and provides moderate aeration. It is suitable for a wide range of crops, offering a balance between water retention and drainage [40].
- Vermiculite:
  - Expands when heated and holds moisture and nutrients effectively. Often used in combination with other substrates to improve moisture retention [41].

There are numerous other types of substrates available, however locally these are the most popular types and were readily available in large quantities.

Choice of the appropriate substrate must take into account the specifics of the chosen crop and hydroponics system. The primary crop chosen for production in this system was Lettuce (as detailed in section 2.6). While available literature exists for comparison of substrate types in horizontal hydroponic systems for lettuce [42], and for vertical traditional farming systems [43], the combination of vertical hydroponics and lettuce substrates was identified as a research gap and experimentation was performed to deduce the optimal substrate (as detailed in section 4.1).

2.5 Edible Plant Considerations

Edible plants differ from other species in numerous ways that alter their parametrisation relative to ornamental species. Edible plants typically require greater amounts of water, nutrients, and sunlight for optimal growth and fruit production [44]. In hydroponic systems, they often require higher-intensity lighting to more closely mimic natural sunlight. However, some species thrive under lower light and less controlled conditions.

Edible plant cultivation often involves more active management—scheduled watering, fertilisation, and pruning aligned with specific harvest times—whereas other species may require less intensive care. Notably, edible plants are frequently subjected to extensive breeding and, in some cases, genetic modification to achieve optimal growth characteristics [45].

Given that hydroponics is a relatively recent cultivation method compared to traditional agriculture, breeding and genetic optimisations have predominantly focused on outdoor farming. Multiple biological parameters could be optimised for indoor growth, adding another layer of opportunity for future research.

Edible plants in hydroponic systems also exhibit specific differences in nutrient content, growth performance, and adaptability. They often thrive within a lower pH range of 5.5 to 6.5 [46]. Moreover, hydroponically grown plants have been observed to exhibit significantly higher levels of nitrogen, phosphorus, and magnesium [47]. Furthermore, precise regulation of nutrient supply is crucial for achieving optimal growth [48].

Hydroponics offers additional benefits for tailoring vegetables to specific nutritional needs, i.e. producing reduced-potassium Swiss chard and spinach for patients with chronic kidney disease [49]. Additionally, bio fortification of edible cacti in hydroponic conditions has been investigated, demonstrating the feasibility of enhancing the nutritional quality of hydroponically grown produce [50].

Through various techniques, cultivators can influence the accumulation of specific elements in edible plant tissues. For instance, Caffagni et al. [51] demonstrated that hydroponically cultivated tomatoes accumulate higher iodine levels in their edible tissues compared to those grown in open-field systems. Furthermore, Law and Exley [52] found that the absence of silicic acid in hydroponic culture allows horsetail plants to grow normally without silica deposition in their tissues.

These examples illustrate that the benefits of hydroponic cultivation extend beyond resource efficiency and space savings.

2.6 Lettuce Cultivation

Preliminary estimates performed in consultation with the partner brewery's restaurant indicated that a medium-scale hydroponic system, if devoted to a single staple crop, could satisfy its total produce requirements. Lettuce was therefore identified as the most suitable candidate from both an end-user and agronomic perspective, since it not only aligns with the restaurant's menu needs but also exhibits several advantageous traits for hydroponic cultivation:

1. *Short Growth Cycle*: Lettuce typically has a relatively short growth cycle of 5-8 weeks, making it well-suited for rapid turnover in vertical hydroponics. [53].
2. *Compact Root System*: The relatively small root system of lettuce makes it ideal for the restricted root zones often associated with hydroponic setups [54].
3. *Consistent Demand*: Lettuce is a staple in salads and numerous dishes, there's a consistent demand for lettuce in urban areas and it does not store as long as other vegetables.

There is a variety of existing literature and experimentation on optimising lettuce production for both indoor and outdoor growing which provides a comprehensive base for consideration of the parameters for this system.

Recently the effects of green light on the growth and development of lettuce plants was studied. Li et al. [55] adjusted the relative amount of green light as a fraction of total photosynthetic photon flux density and a fixed red-to-blue ratio of 4:1. The results showed that $15 - 30\%$ green light replacing red and blue light effectively increased the yield and nutritional quality of lettuce plants. Their study concludes that green light, as part of the photo synthetically active radiation, has high photosynthetic efficiency once absorbed by plant leaves and can regulate plant physiological activities. The study suggests that investigating a moderate proportion of green light can optimise the photosynthesis of plant leaves to maximise the yield in plant production. In this particular design, LED grow lights with green spectrum control were unavailable, so lights offering specific control over the proportions of blue, red, and white were selected instead.

Thakulla et al. [56] researched the effect of temperature on the growth of seventeen lettuce cultivars grown in an NFT Hydroponic System and explored the effects on the growth and quality of lettuce in a hydroponic system. The study results showed that the nutrient solution temperature had a significant effect on the growth and quality of the lettuce. It was found that the optimal temperature range for lettuce growth was between 18 and 22 °C, and that temperatures outside this range negatively affected the plants. The study also found that different lettuce cultivars responded differently to changes in nutrient solution temperature. Overall, the study highlighted the importance of maintaining optimal nutrient solution temperature ensure optimal growth.

With regards to nutrient levels for lettuce, several factors need to be considered. The nutrient concentration and composition in the hydroponic solution perform the role of providing adequate nutrients to the plants without leading to nutritional disorders [57]. Ionic concentration and flow rate of the nutrient solution are determinant variables for nutrient availability and water absorption by the plants in the hydroponic system [58]. Finally, the pH of the nutrient solution can also impact the absorption by the plants, with an optimal range of 5.5-6.5 found by Wang et al. [59] for lettuce and spinach.

2.7 Carbon Dioxide in Hydroponics

Research into the effects of CO_2 enrichment on lettuce and other edible plants has shown significant positive impacts on yield [60, 61, 61–63]. Holley et al. [64] specifically researched lettuce and found that increasing CO_2 concentrations from 400 to 1600 ppm significantly increased fresh and dry weight, with the nutritional components remaining largely unaffected. The research generally shows that moderate CO_2 enrichment will enhance biomass production, but the benefits diminish at higher concentrations. For example, Frantz et al. [65] recorded a 4 fold increase in yield at elevated CO_2 levels (1200 ppm) and increased temperatures, though grappled with issues of tip burn at the higher range. For radish, optimal yield was observed at CO_2 levels of 5000 ppm which is over 10 times higher than normal atmospheric levels [63]. Overall, CO_2 supplementation's optimal benefits appear to occur at moderate levels of enrichment, varying by species and environmental conditions.

The hydroponics industry commonly uses supplemental CO_2 to enhance plant growth in controlled indoor environments. This CO_2 is not only used to replace what plants absorb but also to enrich the atmosphere to levels above normal atmospheric concentrations, boosting yield. IBIS World data shows that the demand for CO_2 in indoor vegetable production is growing, as producers aim to optimise conditions [66]. Commercial CO_2 generators are available for hydroponic purposes which use a variety of different operational methods including bottled CO_2, fossil fuel burning, and chemical reactions.

The production, capture, storage, and transportation of CO_2 are associated with secondary emissions and energy consumption. CO_2 production facilities are typically located near their target markets to mitigate the high costs and logistical challenges of transporting the gas, which must be stored and distributed under high pressure in bulky cylinders [66]. Furthermore, electricity is a key cost driver in CO_2 production, and fluctuations in electricity prices can significantly impact the overall costs and emissions of this process [66].

Given these challenges, the hydroponics industry could benefit from sourcing CO_2 directly from fermentation processes in the manner hypothesised. Future greenhouses could be built adjacent to small breweries, providing a symbiotic relationship between the emissions of the brewery and the supplementation needs of the greenhouse. This approach would also reduce the emissions associated with traditional CO_2 production and transportation. Establishing new hydroponic facilities near breweries would allow for the direct use of CO_2 produced during fermentation, minimising environmental impact and reducing costs. However, there also exists potential for bottling and locally transporting CO_2 from small breweries to urban greenhouses which would avoid the long distances typically involved in transportation from fertiliser manufacturing plants or power plants.

The current practice of using bottled CO_2 in hydroponics effectively enhances plant growth; however, transitioning to a system that utilises CO_2 directly from nearby fermentation sources offers a more sustainable and cost-effective solution for the industry. To achieve this goal, the produced CO_2 must meet minimum quality standards, and be transportable or easily bottled using more economical technologies. To develop a novel hydroponics system

which allows for direct CO_2 ingestion it is important to consider the current methodologies used to produce the gas.

2.8 Production Methods for Bottled CO_2

Bottled CO_2 is used across various industries, including hydroponics, and is primarily sourced from industrial processes. One of the most common methods involves producing CO_2 as a byproduct of the ammonia industry via the Haber-Bosch process, which is used for fertiliser production [67]. Another common source is the capture of CO_2 from underground deposits or flue gases emitted by industrial activities, although the latter is less frequent due to costs [68].

Detailed breakdowns from suppliers regarding the processes used to produce their bottled CO_2 were not publicly available. This lack of transparency implies that the CO_2 could be sourced through any combination of these methods, resulting in highly variable CO_2 emissions associated with their production. The predominant industrial methods currently used include:

- **Natural CO_2 Wells:** In certain geographic areas there are underground reserves of CO_2, which result from natural geological processes. These reserves can be tapped and gas then purified and bottled. However, the location-specific nature of this method and the expensive nature of CO_2 transport makes it less than ideal [69].
- **Combustion of Hydrocarbons:**
  - *Post-Combustion Capture:* CO_2 can be captured after fossil fuels are burned. The flue gas, containing CO_2, water vapour, and other emissions, is first passed through a solvent, typically amine-based, which absorbs the CO_2. The solvent can then be heated to release pure CO_2, allowing the solvent to be reused [70].
  - *Pre-Combustion Capture:* Fossil fuels can undergo gasification, producing a mixture of hydrogen and carbon monoxide. The carbon monoxide will react with water to form CO_2 and more hydrogen. This CO_2 is then separated before combustion occurs, typically using solvents as described above [71].

  - *Oxy-fuel Combustion:* In this process fossil fuels are burned in oxygen instead of air, resulting in CO_2 and water vapour as the primary waste. After condensing the water vapour, pure CO_2 remains which is then compressed [72].

- **Chemical Production:** Certain chemical reactions, such as the production of ammonia or the reaction of carbonates with acids, produce CO_2 as a byproduct. These byproducts can be captured, then purified, and bottled. This method supplies a significant amount of bottled CO_2 in Australia [66, 73].

- **Bio energy with Carbon Capture and Storage (BECCS):** BECCS involves burning biomass for energy and capturing the resultant CO_2 emissions. Since the biomass absorbs CO_2 during growth, the process can be carbon-neutral, making it an environmentally friendly option for CO_2 production. However, it is not yet a fully matured or commonplace process [74].

Utilising CO_2 sourced directly from fermentation processes has the potential to offer a more sustainable and cost-effective alternative to conventional methods. This approach may also reduce transportation and logistical expenses associated with procuring CO_2 from geographically fixed natural wells, while supporting a circular economy by re-purposing waste gas streams from facilities such as breweries. By incorporating fermentation-derived CO_2, the hydroponic industry could potentially enhance its environmental performance and lower operational costs. However, realising these benefits will depend on the development and implementation of effective brewery carbon-capture and purification systems.

2.9 Brewery Carbon Capture

CO_2 is a natural byproduct of the fermentation process used in the production of alcoholic beverages such as beer and wine. This CO_2 can be captured, purified, and bottled, providing a consistent and local source [75].

For larger breweries producing hundreds of thousands of barrels annually, CO_2 recapture systems are very common. These systems represent significant capital investments, often costing in the seven-figure range [76], and are offered by major industrial suppliers such as

GEA and Atlas Copco. The economies of scale in large breweries make these systems more feasible compared to smaller operations. Larger breweries can justify the high upfront costs because they have higher CO_2 purchasing needs, allowing the system to pay for itself more quickly through savings.

Systems such as those provided by GEA are designed to handle large volumes of CO_2, with capacities ranging from 100 to 8,000 kg of CO_2 per hour. These systems are typically installed in breweries that produce between 200,000 and 16 million hL of beer annually. The investment in such systems is driven not only by potential cost savings but also by the need to maintain a stable CO_2 supply, which is crucial for various brewing processes [77–79].

Breweries that capture their own CO_2 during the fermentation process can offset a significant portion of their CO_2 needs for various operations such as purging tanks, keg filling, and carbonation. However, whether this captured CO_2 is sufficient to meet all their needs depends on several factors such as the size of the brewery, the efficiency of the CO_2 capture system, and the brewery's specific CO_2 consumption requirements.

As an example breweries like Sierra Nevada and Alaskan Brewing Company have implemented CO_2 recovery systems that allow them to capture and reuse the CO_2 that is generated during fermentation, significantly reducing their reliance on external suppliers. Sierra Nevada has become largely self-sufficient in its CO_2 used for packaging, transporting beer, and even using it in their own taproom. However, they occasionally still need to purchase additional CO_2 depending on their production demands and product lineup changes [76, 80].

Smaller breweries or those with high CO_2 demand for products like hard seltzers (which do not generate CO_2 during production) may find that their captured CO_2 is insufficient for all their needs. For example, Maui Brewing Company, despite capturing a substantial amount of CO_2, still relies on external suppliers for about 30-35% of their CO_2 needs as they continue to grow [80, 81].

A CO_2 recovery system doesn't capture all the CO_2 generated during fermentation. The complexity of the system, maintenance requirements, and potential downtime can also

impact how much CO_2 is effectively recaptured and reused [76].

FIGURE 2.1: Industrial carbon capture unit (image source: [2]).

While CO_2 recapture systems offer significant benefits, including reducing a brewery's carbon footprint and ensuring a more reliable CO_2 supply, they are more accessible to larger breweries due to the high initial costs and the economies of scale that come with larger production volumes. This is not to say that CO_2 recapture technology is mutually exclusive with the proposed concept, as the exhaust gasses from the CO_2 recovery system could even be sufficient to enrich the growing environment, though it effectiveness would be dependant on the variables of both the chosen brewery and greenhouse.

Analysis of current brewery carbon capture systems presents three primary considerations:

Conceptual CO_2 Cycle: Brewery operations both produce and consume CO_2, creating a delicate balance. Typically, breweries function as net consumers of CO_2 or strive for self-sufficiency, but rarely do they act as net producers.

Economic and Technical Barriers: Carbon capture systems are expensive to install and maintain, resulting in a significant proportion of small breweries not utilising the technology. Additionally, these systems are not designed to capture 100% of a brewery's emissions. Consequently, some quantity of CO_2 remains available for harvest at all breweries.

Potential for Low-Cost Harvesting Systems: Developing a harvesting system that is low cost and easily installed could tap into an existing source of CO_2 at breweries, with the

available volume likely inversely proportional to the brewery's size (depending on equipment and brewing methodology). It is inferred that many small breweries lack carbon capture technology, making them ideal targets for a low-cost symbiotic greenhouse. Breweries that already have some form of carbon capture are not necessarily excluded, as the expansion of their production over time would result in increased CO_2 emissions unless their carbon capture systems are equally scaled. Given cost and space pressures, such scaling becomes less feasible for smaller breweries.

With surging popularity of small breweries in Australia, many do not perform carbon capture at all. These breweries would be available for integration with hydroponics if a suitable system can be developed to enable it.

Background research identified one case of a similar relationship in which Denver Beer company, which produces about 25,000 barrels a year, sells excess recaptured CO_2 to a local cannabis-growing operation [76]. This facility uses a commercial grade carbon capture system to purify and bottle the CO_2 before delivering it in tanks.

2.10 Summary

Among the many critical factors for optimising plant growth in hydroponic systems, CO_2 control is used to limit ventilation and conserve energy, as well as enrich the environment to increase yield. Breweries offer an underutilised source of CO_2, as they generate significant amounts during fermentation. While large breweries often capture and reuse this gas, smaller breweries frequently release it as waste. This creates an opportunity for symbiosis: hydroponic systems that require CO_2 for plant growth can utilise the waste CO_2 produced by small to medium-sized breweries, forming a mutually beneficial relationship.

A review of literature on modern automated hydroponic systems underscores the recent advancements in environmental control, and resource optimisation. However, the size, and duration of experiments assessed limits their reliability. IOT systems described in current literature have been able to automate aspects of a hydroponic control system but have not been tested at a larger scale, or for long duration's. By performing this type of testing it will be possible to reveal edge cases and design issues required for full commercial application.

The potential benefits of directly using CO_2 from brewery waste in hydroponics could offer a sustainable and lower-cost alternative to traditional bottled CO_2, which is often sourced through energy-intensive industrial processes. By directly using CO_2 from brewery fermentation, a hydroponic system could reduce its environmental impact while minimising costs related to CO_2 procurement.

In order to realise this novel goal there are a large number of technical challenges and research hurdles to be overcome. This leads to the following research questions which are addressed in this thesis:

1. *Can a commercial-scale hydroponic system be created within a working brewery using an IoT-based automation system to both control environmental variables and dynamically introduce brewery CO_2 for enrichment?*

2. *What insights can be gained from fully integrating the IOT control system with advanced data capture methods, and performing experiments at a larger scale?*

3. *To what extent can raw, unprocessed CO_2 from breweries be practically and efficiently utilised in hydroponic systems without requiring energy-intensive processing?*

Chapter 3

Methodology

This chapter details the architecture and methods used to implement the IoT-controlled hydroponic system and brewery CO_2 prototype. The design variables considered in this chapter directly address the first research question of whether a commercial-scale system can be created and controlled in this context, and lay the foundation for the data capture and experimental insights required for the second and third questions.

3.1 Design of a Novel Hydroponic System

In the initial exploration of constructing a modern and integrated hydroponics system, a complex and intertwined parameter space was encountered, with over 60 parameters identified through preliminary research across various system aspects, as detailed in Chapter 2. Each parameter has the potential to influence the efficiency and output of the hydroponic system in some manner. Addressing this entire parameter space simultaneously is impractical.

To address this challenge, a strategic approach was implemented to prioritise the parameter set. The methodology involved identifying the variables which have the most significant impact on plant growth, system efficiency, and sustainability, as described in subsection 2.3. This prioritisation was based on a combination of empirical evidence, consultation with hydroponics suppliers, and domain knowledge availability.

Parameters such as nutrient concentration, pH levels, lighting schedules, and CO_2 concentration were highlighted as having significant effects on plant health and yield in many papers. By focusing on optimising these key parameters, the most substantial improvements in system performance can be achieved while maintaining manageable complexity in the experimental setup.

Another aim in designing the architecture for the enclosure's control system was to create an efficient yet economical automation solution. Modern agriculture, especially hydroponics, demands precise control over various parameters for optimal performance. Logic controls and automation systems underpinned by software such as ours, offer a high level of granularity and enable dynamic adjustments based on real-time data. However, achieving this often comes at a substantial financial cost when using proprietary systems or specialised hardware.

This approach aimed to challenge the conventional trade-off between cost and functionality by integrating affordable, off-the-shelf components into the control system. Firstly, the objective was to ascertain the operational boundaries of these economical components in an agricultural setting. Secondly, an assessment of the reliability of these systems over a longer period was performed. While many existing projects using similar architectures function effectively in laboratory environments, consistency and durability over extended periods are crucial for hydroponics, where any interruption can cause significant damage to the crop.

3.2 Site Context

The system described was built on premises at an operational brewery located in Sydney, Australia. It is situated in a dense commercial environment that contains a number of different operational areas over a two level warehouse. The host organisation partnered with us for this research project in order to experiment with the practicality and feasibility of urban based vertical hydroponic farming and CO_2 recycling. The brewery contains an operational restaurant and bar which can consume the food produced directly negating any transport and refrigeration emissions directly associated with typical farming. Further, the

facility has an abundant 100 kW rooftop solar system which provides ample power to run the various electrical components housed in the hydroponics enclosure. A diagram of the building layout is shown in Figure 3.1 to provide context to the location of the hydroponics system in relation to the other areas of the facility.

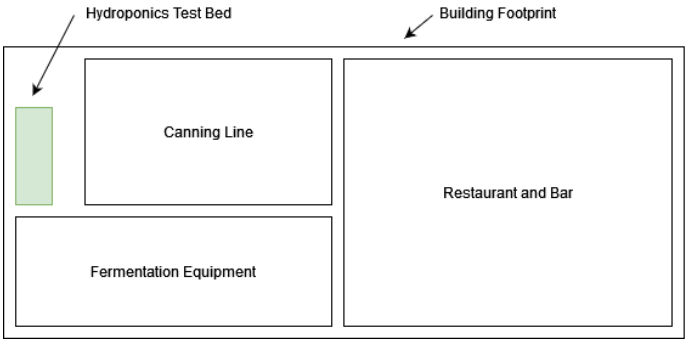

FIGURE 3.1: Facility layout diagram.

Given the specifics of the project listed above a number of parameters for the system design were fixed and unable to be manipulated:

- Height, width, and length of the enclosure (available space).
- Maximum power consumption (10 amp).
- Location inside the building (inclined on a ramp).
- Enclosure front material was chosen to be glass in order to allow participants in brewery tours to observe the plants growing.
- Enclosure construction materials (cost).

Fixing these parameters governed some of the overall conceptual design which resulted in several challenges and non-optimised features. These constraints, while challenging, provided a set framework within which the hydroponic system could operate, shaping both its strengths and limitations within this specific context.

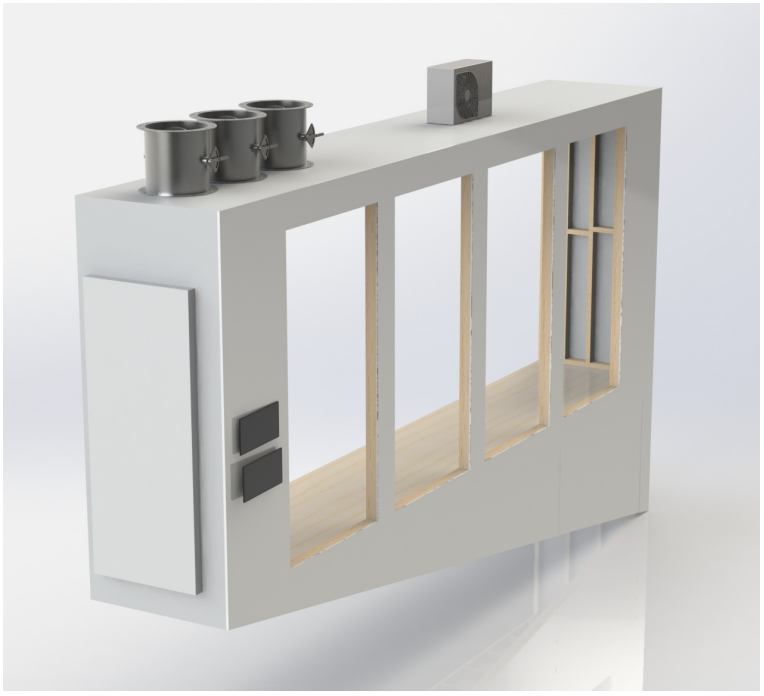

FIGURE 3.2: CAD model of enclosure.

3.3 Temperature Control

The temperature of the nutrient solution in hydroponic systems plays a pivotal role in plant health and productivity. This parameter, often overlooked in comparison to nutrient concentration or pH, can profoundly impact plant physiology and metabolism [82].

Optimal temperature for nutrient solutions presented in literature are varied from approximately 14°C to 25°C depending on plant species [56], [83], [84], [85]. When optimised plants can effectively uptake essential nutrients, as both nutrient solubility and root metabolic activity are optimised.

Conversely, sub optimal temperatures can usher in a myriad of challenges. Cold nutrient solutions, for example, can reduce root metabolic rates, making plants more susceptible to root diseases due to decreased oxygen uptake. Cold solutions can also reduce nutrient uptake efficiency, leading to nutrient deficiencies even if the nutrient concentrations in the solution is within range [86]. On the other end of the spectrum, excessively warm nutrient solutions can be equally detrimental. Elevated temperatures can reduce the solubility

of oxygen in water, potentially leading to hypoxic or anoxic conditions for the roots. Such conditions can compromise root function and can exacerbate vulnerabilities to root pathogens. [87].

It is also noteworthy that the temperature of the nutrient solution affects not only the direct uptake of nutrients but also the microbial ecology within the hydroponic system. Beneficial microbes, which can aid in nutrient assimilation or compete with potential pathogens, have their own optimal temperature ranges. Thus, maintaining the solution temperature within optimal limits supports a healthy microbial balance, which in turn benefits plant health and reduces maintenance with regard to algae growth.[88].

Temperature monitoring within the enclosure was achieved by deploying an array of sensors placed inside and outside to track various critical points. The specifics of these sensors are detailed in Table 3.1.

TABLE 3.1: Temperature sensors specification table.

Item	**Type**	**Sensor Model**	**Manufacturer**
Nutrient solution tank	Water	PT1000	Atlas Scientific
Return nutrient line	Water	PT1000	Atlas Scientific
Grow pod centre	Air	DHT11	Adafruit
Grow pod air-conditioner outlet	Air	SHTC3	Adafruit
External to grow pod	Air	DH11	Adafruit
Inside hydraulics cupboard	Air	DHT11	Adafruit

These sensors provide real-time data on the temperature at those key locations and allow for adjustments as required to be made either manually or automatically in the control interface.

To control the air temperature in the enclosure, a reverse cycle air conditioning system was installed, which also helps to manage humidity levels, which can influence plant transpiration rates and overall health. The specifications for the air conditioning system used can be found in Table 3.2. The air conditioning units maximum cooling power was chosen using a 1-1.5kW per 10 m^2 estimation formula which is commonly used in Australia for domestic applications. Our testing showed that despite the growth pod size being only 12 m^2, and the air conditioner having a maximum capacity of 3.2 kW it was still insufficient in the peak of summer.

TABLE 3.2: Air conditioner specification table.

Indoor Unit	SLZ-M25FA-A.TH
Outdoor Unit	SUZ-M25VAD-A.TH
Panel Unit	SLP-2FA
Power Supply	230V / 1Ø
Cooling	
Capacity [Min - Rated - Max]	1.5 - 2.5 - 3.2 kW
Total input [Rated]	0.65 kW
AEER/EER	3.73 / 3.85
Star Rating	3.0
Running current [Rated]	3.25 A
Air Volume (In) [Lo-Mid-Hi]	108-125-142 L/s
Heating	
Capacity [Min - Rated - Max]	1.3 - 3.0 - 4.5 kW
Total input [Rated]	0.78 kW
ACOP/COP	3.75 / 3.85
Star Rating	3.0
Running current [Rated]	3.77 A
Air Volume (In) [Hi]	108-125-142 L/s
Refrigerant	
Pipe Size	ø6.35 mm and ø9.52 mm
Operating Range	
Cooling	-10 to 46 °C
Heating	-10 to 24 °C

Extensive measures were implemented to ensure the enclosure remained as airtight as possible, thereby facilitating the accurate measurement of internal environmental variables during experimentation:

- The sub-floor was sealed with urethane sealant and overlaid with tiles.
- Air conditioning penetrations were sealed against ceiling panels made of veneer-coated plywood, which were also sealed at the junctions.
- A custom-made door featured a double-lip rubber seal around its perimeter was installed for entry.
- Fixed glass glazing panels were installed with rubber gaskets to seal around the perimeter, and sealed with silicone at the intermediary junctions.
- Drainage penetrations included an S-trap to prevent air entry.

- All electrical and plumbing penetrations were sealed with silicone.
- Ventilation ducts were equipped with electronic damper valves that closed automatically when not in use.

3.4 Hydraulic System

The hydraulic system for the enclosure was developed to provide redundancy as well as utilise both rainwater and freshwater for its intake. The main components of the hydraulic design are detailed in Figure 3.3.

The nutrient pumping system is setup using 2 centrifugal radial flow pumps (Sensen HQB-5500) which can provide a head height of 5.5m and flow 6800 LPH. Because these pumps do not contain any variable speed adjustment a ball valve was placed on the pressure side of the pump before the dripper outlets to allow the operator to adjust the flow through the dripper system by bleeding water back into the main reservoir to lower line pressure. This configuration worked well for the nutrient supply during operation of the enclosure and allowed for accurate flow rate calibration through the attached pressure sensor, which provided a feedback mechanism to determine if flow was within range.

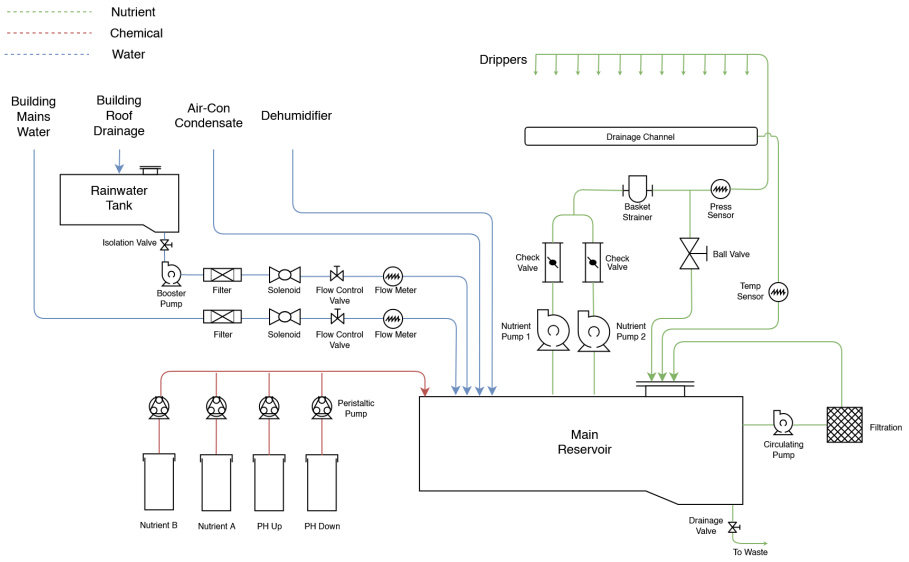

FIGURE 3.3: Hydraulic system diagram.

Check valves are positioned immediately after each pump meaning that in the event of a failure of one pump the other can be started without manual intervention and water will not flow through the failed pump. In this configuration pumps can be replaced with the system running which we determined an important design parameter to ensure reliability. Plants can deteriorate rapidly when the nutrient solution is disrupted because the plants are entirely reliant on the solution for hydration. Depending on the chosen substrate the available water will evaporate very quickly under the artificial lighting. In traditional soil cultivation the soil acts as a buffer, storing some nutrients and moisture for plants. [89].

The nutrient reservoir is made of food grade polyethylene plastic, which has been roto-molded into a rectangular shape. The container is rated as holding 450L with dimensions of 1220mm x 610mm x 610mm. This container was chosen by considering a number of factors. We were unable to find any literature which could scientifically prescribe the size required for the number of plants in the enclosure. Speaking to local hydroponics business owners an "industry rule of thumb" of 1.5-2L of water per plant for small plants was considered. This was not feasible with the space restrictions available and it appeared as if this value is aimed at larger plants, so a compromise of 1L minimum nutrient capacity for each plant in the main reservoir was chosen.

After initial commissioning it was found that small gaps around the edges of the lower enclosure allowed light to be transmitted into the cupboard housing the reservoir, and even a very small amount of light was enough to cause large algae blooms. To counteract this an ultraviolet steriliser and external filter (Giantz 2400L/H Aquarium filter) was added adjacent to the tank which performed well at keeping algae growth under control without the need for further water treatment chemicals.

In order to reduce water usage we employed an HVAC condensate recovery line which leads up the to the air conditioning unit on the roof of the enclosure and discharges back into the main reservoir.

In Figure 3.4 a photograph of the main components comprising the system can be seen. In order to create a seal between the grow pod and external environment the drainage system penetrations comprise an s trap which blocks any air entering the enclosure through the drainage system. The nutrient supply bypass valve which regulates the flow rate is also

visible, and an added benefit of this configuration is heavy oxygenation occurs as the solution is injecting back into the reservoir.

There are 3 float level sensors used in the system: these sensors trigger the introduction of fresh water from either the rainwater tank or mains water supply. The system oscillates the water level around the middle sensor. It introduces water until the middle sensor is triggered high, then when triggered low through usage a software time delay activates. The other two sensors are programmed for triggering a danger low and danger high alarm, and both shutdown the automatic levelling system and turn off all pumps and solenoids if they are triggered. Sensor redundancy in this setup was considered important when utilising software based logic. In the event there is an issue with the software control over the tank water level the relay wiring is setup such that water solenoids cannot activate if the high water level float is up (open circuit).

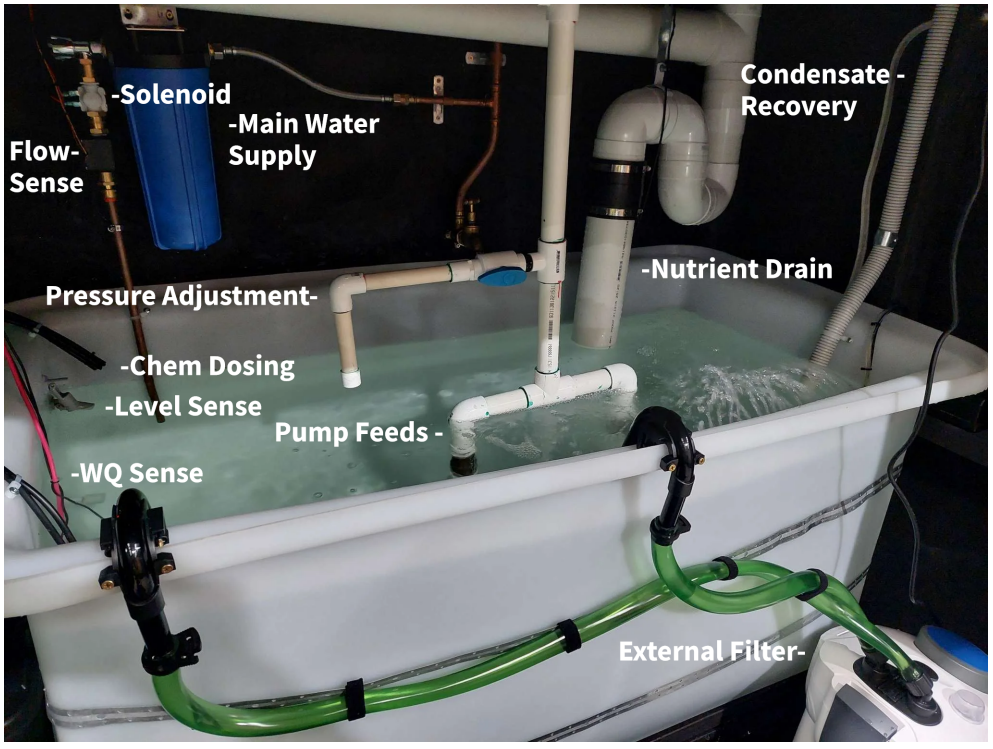

FIGURE 3.4: Hydraulic system photograph - Photograph by the author (2024).

3.5 Lighting

Hydroponic systems rely on a controlled environment where ideally light intensity and spectrum can be carefully managed. These two parameters play an important role in optimising plant growth, morphology, and metabolic processes [55].

PAR or "photo-synthetically active radiation" is the range of light wavelengths (usually between 400-700 nm) that plants use for photosynthesis. It encompasses the blue and red regions of the light spectrum that plants predominantly utilise for their growth. The measurement of PAR:

1. *Determines Usable Light*: Not all wavelengths of light are beneficial for plant photosynthesis, and PAR distinguishes the useful light from the total light spectrum [31].
2. *Quantifies Light Intensity*: PAR is often measured in terms of photosynthetic photon flux density (PPFD), which gauges the number of photons in the PAR range received over a specific area in a given time frame. Hence, PPFD becomes an important variable to consider in the system. [31].

The optimal PPFD for growing lettuce is contentious depending on the author but typically falls within the range of 200 to 400 µmol/m²/s. However, the story does not end simply with attributing a number, this range is ideally incremented during the growth in a phased manner:

- **Seedlings and Early Growth:** Lettuce seedlings and young plants often recommend a lower PPFD, around 150-200 µmol/m²/s. [90].
- **Vegetative Stage:** As the lettuce plants grow, they can benefit from a more moderate PPFD. A range of 300-400 µmol/m²/s for example.[90].
- **Mature Plants:** For mature lettuce plants, maintaining a PPFD within the range of 500-600 µmol/m²/s can be recommended.[90].

Adjusting the light intensity within these ranges can help the operator optimise growth, improve yield, and ensure healthy development of the lettuce plants. Understanding the role of PAR and manipulating light intensity can even influence plant morphology and flowering times [90].

Environmental factors influencing PPFD directly are scattering and the distance from the light source.

The scattering of light, including PAR, can be attributed to various factors:

1. *Media Interactions*: As light travels through different media, such as air or water, it can scatter because of the differences in refractive indices, thus the lens design and material are important for this. [91].
2. *Obstacles*: Physical obstacles, such as dust particles, water droplets, or structural elements in a hydroponic system, can scatter incoming light. [92].
3. *Wave Effects*: Light, being a wave, has properties such as reflection, refraction, and diffraction, all of which can contribute to scattering [93].

The intensity of PAR (quantified as PPFD), is inversely proportional to the square of the distance from the light source, according to the inverse square law:

$$I \propto \frac{1}{d^2} \tag{3.1}$$

Where I is the light intensity and d is the distance from the source.

The implications of this relationship are important for hydroponic systems:

1. *Rapid Intensity Drop-off*: As the distance from a light source increases, PAR intensity drops off rapidly, making it essential to place plants at an optimal distance to ensure sufficient light exposure. [94].
2. *Uniformity Challenges*: Ensuring consistent light distribution can be challenging, especially in large hydroponic setups. The inverse square law's effects mean that plants closer to the light source receive significantly more light than those further

away. Strategies such as using reflectors or adjusting the position of light sources can help mitigate these challenges.

From a design perspective it is important to consider the potential impact of PAR levels on plants:

1. *Photosynthesis Enhancement*: Higher PPFD generally promotes photosynthesis up to a certain threshold, beyond which photo inhibition can occur. Rajasekaran and Blake demonstrated that plant growth regulators like ABA, Ambiol, and polyamines enhanced elongation growth but also increased photosynthesis rates under drought conditions, demonstrating the potential for increased PPFD to enhance photosynthesis even under stress. [94].

2. *Growth Rate Determination*: Optimal light intensities can maximise growth rates, while too low or too high intensities can stifle growth or cause damage to plant tissues. Cardona emphasised the importance of balanced light intensity for optimal plant development. [95].

3. *Morphological Impact*: PPFD influences plant architecture, with lower intensities leading to elongated stems and larger leaf areas, a phenomenon termed shade avoidance. This was observed directly in our experimentation and is one of the reasons direct comparisons are so difficult between experiments. Paradiso elaborated on this and demonstrated how plants alter their growth in response to light conditions, with significant changes in morphology under different light intensities. [96].

4. *Photosynthetic Efficiency*: Blue (400-500 nm) and red (600-700 nm) regions are most effective for photosynthesis. This appears to be why early LED-based grow lighting used only red and blue LEDs. Recent advancements have shifted towards full-spectrum and UV lighting to mimic natural sunlight and further improve photosynthetic efficiency. Cardona et al. reviewed how enhancing the light reactions of photosynthesis through targeted wavelengths can improve crop yields and efficiency. [95].

5. *Morphological Responses to Colour*: Blue light influences stomatal opening, phototropism, and suppresses elongation growth. Red light, conversely, can stimulate

stem elongation and flowering. Iluz et al. discussed the effects of fluctuating light on photosynthesis and plant growth, highlighting how different light spectra impact morphological responses. [97].

6. *Photo Periodic Flowering*: Plants rely on the red to far-red light ratio to sense night length and determine flowering times. Thus, with the use of spectrum control, growers can arbitrarily stimulate flowering by mimicking this response. Shah et al. explored how plant growth regulators can mediate changes in growth and photosynthesis, which can be linked to light spectrum manipulation for flowering control. [98].

This is intended as a summary of some of the biological mechanisms at play, rather than an exhaustive list.

For the lighting specification it was required that the lights be controllable using an open digital protocol to allow them to be embedded into the larger overall system. California Lightworks Solar System 550 LED grow lights were chosen based on this and local availability, with the specifications shown in Table 3.3.

These lights use an RS232 control protocol and were able to be adapted into the architecture utilising a USB to RS232 converter to set the colour spectrum and brightness.

3.6 IOT Based Logic and Control

To capture large amounts of data, a control and data capture system was designed using open-source products. The fully integrated nature of the data and control system outputs builds upon examples from existing literature, enabling comprehensive management and monitoring of all critical parameters discussed above.

The Raspberry Pi 4b functions as the primary micro-controller unit (MCU) within the networked system, handling the integration and management of various devices and sensors. The MCU is responsible for controlling an 8-channel relay board, which facilitates the regulation of low voltage devices such as damper valves, indicator lights, and 12V air

Table 3.3: Light system specification table.

Specification	**Details**
Efficiency	2.51 umol/j
Power Consumption	0 - 400 W
Light Output - PPF	1,005
Spectrum Control	Digital/Programmable
Auto Voltage	90-277V
Maximum Current	3.3A@120V, 1.65A@240V
Frequency	50-60 Hz
Heat Output - BTU	1280
Operating Temperature	0-107 F
Power Factor	0.95
Dimensions	18" x 8.5" x 4"
Weight	13 lbs
Coverage Area - Bloom	Up to 6' x 6'
Coverage Area - Veg	Up to 6' x 6'
LED Lifetime Rating	50,000+ hours
Warranty	5 Years
Thermal Management	Active
Dimming	3 Channel
Cord Length	6 Feet
Data Connection	RJII
Certification	UL, CE

ventilation fans. Node-Red is used as the software based logic controller, with Grafana acting as the live monitoring system for the enclosure. Various flows were designed to automate different aspects of the system. We opted to separate each logical control function into a separate flow and tie these together with context variables and cross flow triggers:

- Camera Control
- Chemical Dosing
- Switching
- Environmental Monitoring
- Lighting
- System Functions
- Import Data

- Export Data
- Tank Level Control
- Error Logging
- Calibration

The MCU performs the roles of network server, and logic controller, orchestrating the entire network of devices and sensors performing tasks such as IP assignment and internet connection sharing from the facilities connection via Ethernet. For enhanced flexibility, wireless smart switches were also included. These switches allowed for the remote activation of mains appliances easily and additionally provide power usage statistics. Although they were reserved only for devices which did not need to be frequently restarted due to the short delay in state change.

In the initial stages of system development, flexibility was prioritised due to uncertainties surrounding the exact number and types of sensors required. To facilitate the rapid integration of new sensors as required, an Arduino Mega was interfaced with the Raspberry Pi via a serial connection. By utilising the Firmata protocol, direct access to the 5V pins from the central MCU was enabled, streamlining the incorporation of 5V sensors from suppliers like DFRobot and expediting the deployment process.

The network infrastructure included a Power over Ethernet (PoE) switch, which was used to power additional Raspberry Pi nodes but also support the two kiosk displays. These displays provided real-time data visualisation and system status updates directly within the brewery environment for the user. They were configured to startup in full screen kiosk mode and display custom Grafana dashboards.

The control over lighting infrastructure, incorporating features such as dimming and adjustments to the colour spectrum, was also integrated into the overall program. The control was achieved through the use of a USB to RS232 adaptor which was able to send control packets to the daisy chain of lights.

Data collected across the network was aggregated locally in InfluxDB. This data was then subsequently transferred to the cloud via a zero-configuration virtual private network. This

setup allowed remote access and two-way control over the entire system. A photograph of the control systems main board is displayed in Figure 3.5, while Figure 3.6 shows the relevant system schematic.

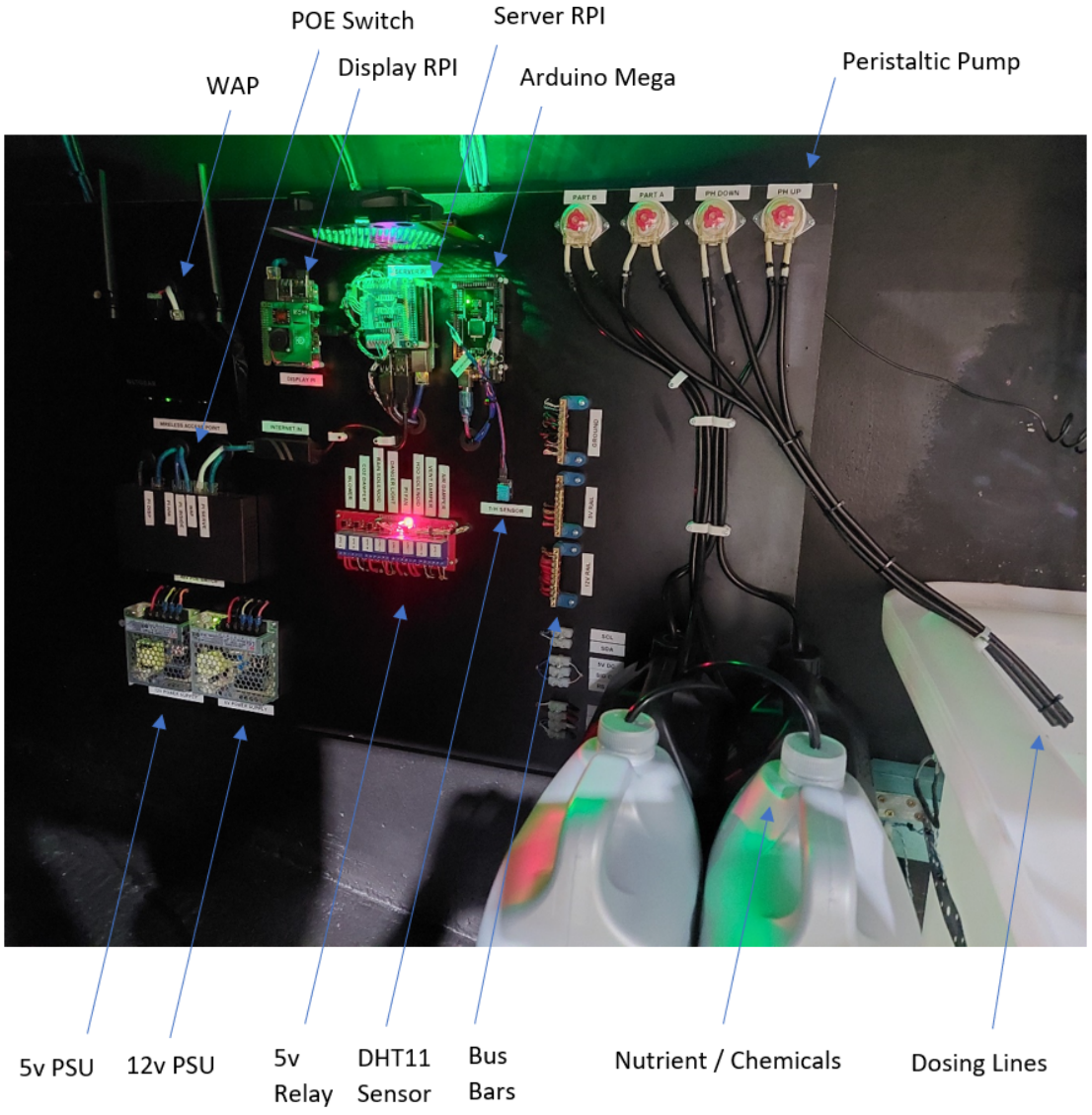

FIGURE 3.5: IOT hardware photograph - Photograph by the author (2024).

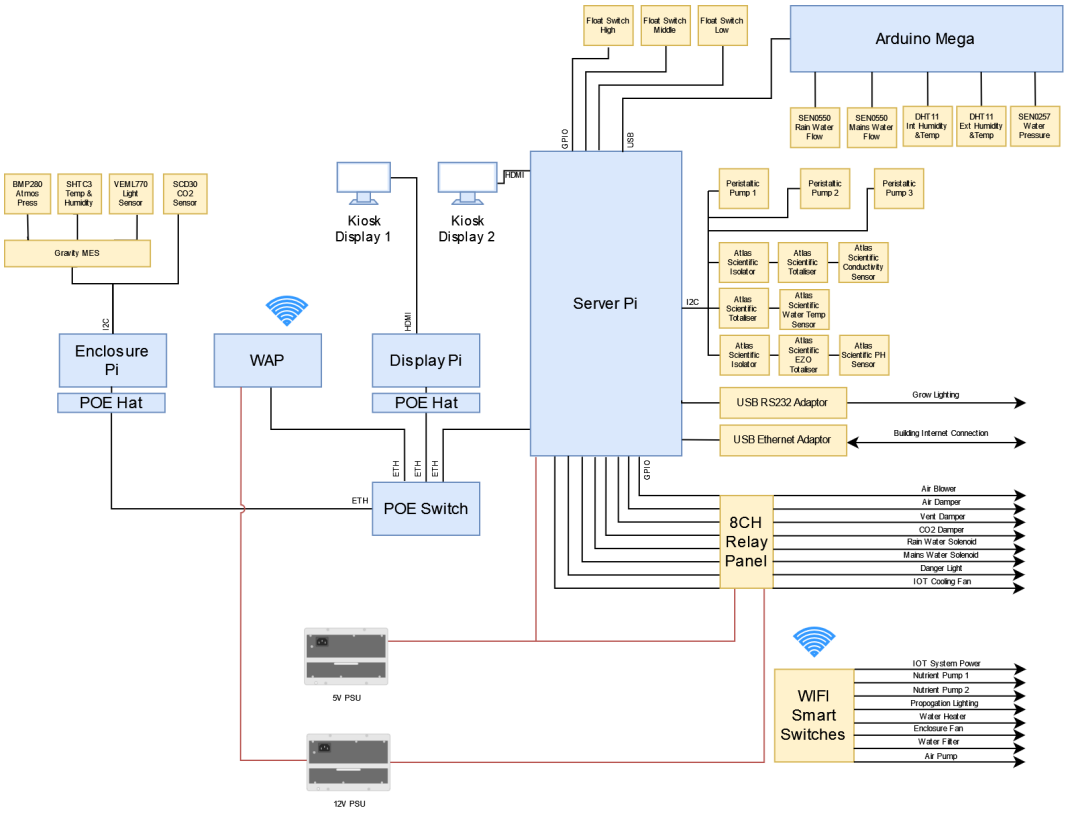

FIGURE 3.6: IOT system diagram.

3.6.1 Node-RED Chemical Dosing Flow

Figure 3.7 illustrates the Node-RED flow which governs automated nutrient and pH correction. This system was developed in order to maintain system expandability and avoid any vendor lock-in which may occur using proprietary controllers. The process operates as follows:

1. **Sensor input**

   Every 15 seconds the Atlas-Scientific probes publish *pH*, *EC (conductivity)* and *nutrient-tank temperature* via the connected I2C sensors. Each new reading enters a short sliding-window queue (length = 10). When the queue fills, the node forwards the 10-sample block to the relevant regulator.

2. **Smoothing and state storage**

   The *pH Regulator* and *EC Regulator* nodes replace the previous smoothed value

(stored in a Node-RED *flow* variable) with the average of the new 10-sample block. This moving-average filter removes sensor noise and prevents the system responding to outliers.

3. **Min–max decision logic**

   Each regulator compares the smoothed value to user-defined upper and lower bounds (e.g. pH 5.5–6.5, EC 1.2–1.6 $\mathrm{mS\,cm^{-1}}$).

   - If the value is *inside* the band, no action is taken.
   - If it is *below* the band, the "dose-low" output fires (pH-up or Nutrient B).
   - If it is *above* the band, the "dose-high" output fires (pH-down or Nutrient A).

4. **Interlock / anti-oscillation layer**

   All dosing commands pass through an *Interlock Controller*. In **Auto mode** the interlock enforces a 30-minute refractory period after any dose to prevent rapid cycling. In **Manual mode** (selected on the enclosure's LCD touchscreen) this lock is bypassed so an operator can jog the pumps repeatedly when first filling or re-calibrating the tank.

5. **Pump actuation**

   Approved commands drive one of four 12 V peristaltic pumps (pH-up, pH-down, Nutrient A, Nutrient B) via a relay board. The pulse length is adjustable (default 3 s $\approx$ 25 mL).

6. **Feedback and data logging**

   Each authorised dose writes a record to InfluxDB: timestamp, pump ID, pulse length, and pre-/post-dose pH or EC. These tags let the operator correlate "dose volume vs. measured shift" and fine-tune both the pulse length and the 30-minute lockout in Grafana.

In practice this hierarchy—*sensor queue* $\rightarrow$ *smoothing* $\rightarrow$ *min–max check* $\rightarrow$ *interlock* $\rightarrow$ *pump pulse*—keeps the system stable, avoids run-away dosing, yet still gives staff one-touch manual control when needed.

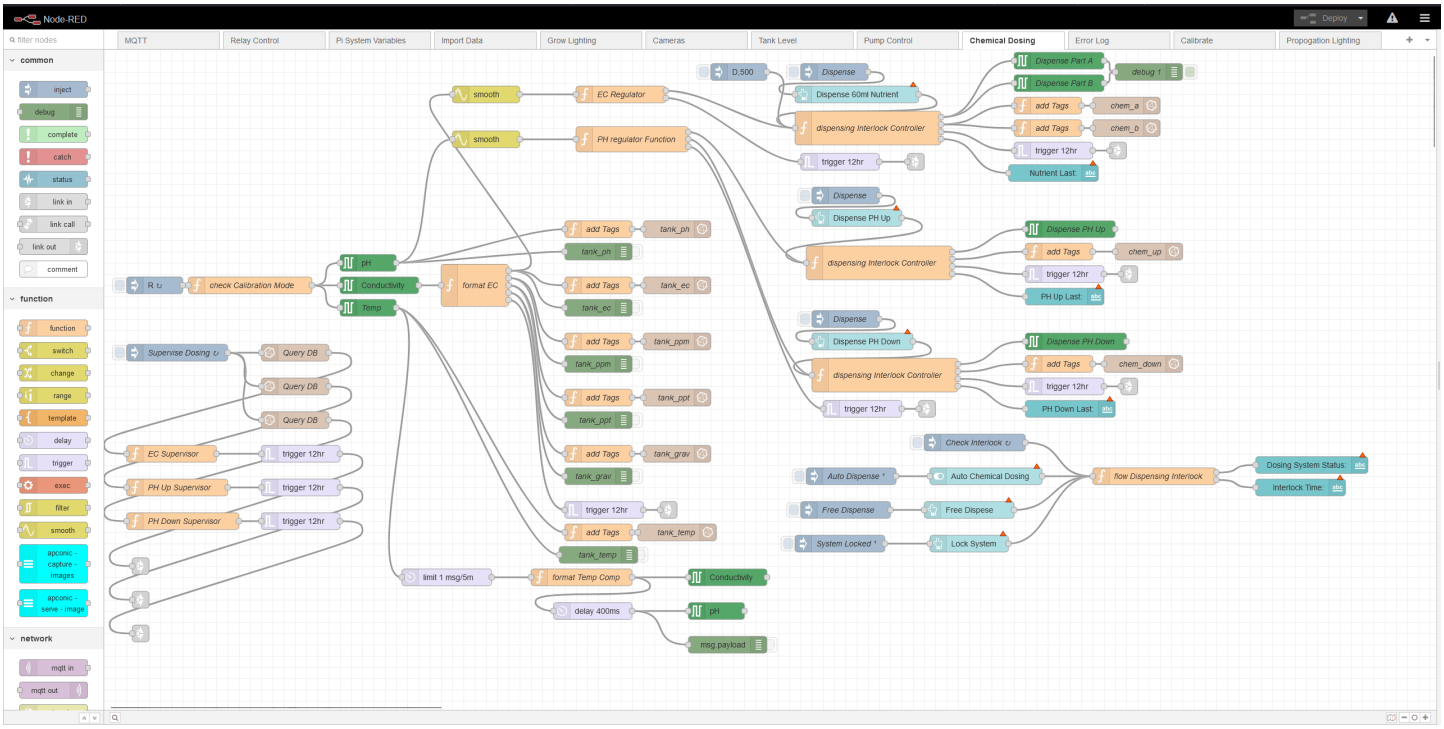

FIGURE 3.7: Node-Red chemical dosing system flow.

3.7 MQTT Data Import

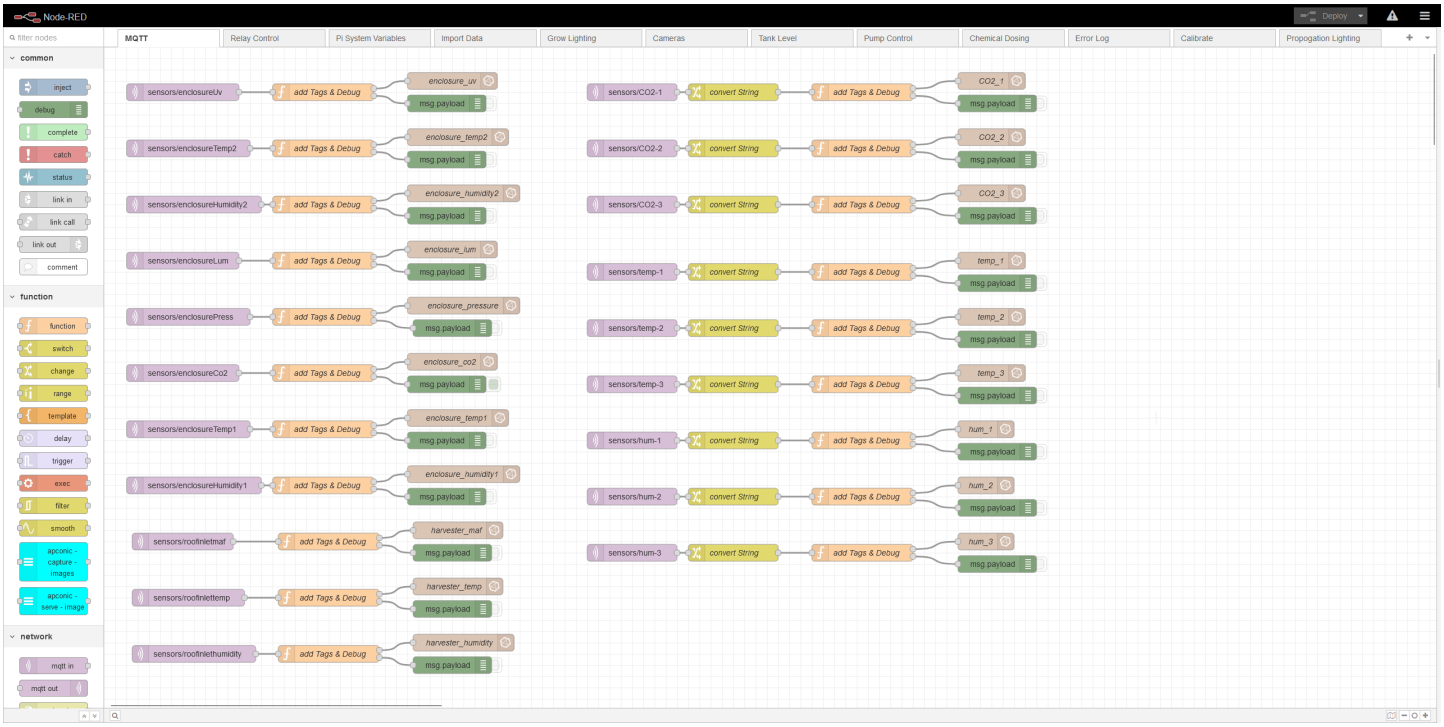

FIGURE 3.8: Node-Red data import flows.

3.8 Harvesting System

The CO_2 harvesting system was designed to scavenge byproduct gases from the fermentation processes and consists of three main components, the spunding valve adaptor, CO_2 manifold, and control unit (with damper valve assembly).

The initial collection mechanism involved a custom spunding valve adaptor, which securely fits onto the spunding valve's glass inspection bowl on the fermenter. For the proof of concept testing a rubber seal was not incorporated as some leakage was considered acceptable, but future versions should seal completely to eliminate oxygen from entering the CO_2 system. As the CO_2 exits the fermenter, it flows through the typical spunding valve and from there into the adaptor and corrugated flexible hosing attached to it. Each fermenter in the brewery can be equipped with one of these adaptors, allowing for scalability across multiple fermentation units. To prevent unintentional gas escape from other adaptors, each adaptor is fitted with a ball valve, enabling shut-off when not in operation. The low operating pressures, sometimes as low as 2 PSI, necessitate a system design with very low resistance to gas flow. Ideally, a one-way valve would be incorporated instead of a manual ball valve to make the system more user friendly. Unfortunately, suitable one-way valves that operate under such low pressures were not readily available.

Once collected, the CO_2 was channelled through the corrugated hose into a manifold constructed from 25mm poly pipe. This manifold serves as the central conduit, directing CO_2 from each fermenter along a path that ascends to the brewery's ceiling and then extends across to the hydroponics enclosure. This layout allows for multiple fermenters to be connected to the manifold and the manifold to be extended as required if future needs require. We opted to run the pipework along the ceiling so that any foam or liquid that might be drawn into the system would have ample time to flow back down the pipework over the long traversal. This did not function as anticipated and is covered later in Chapter 5.

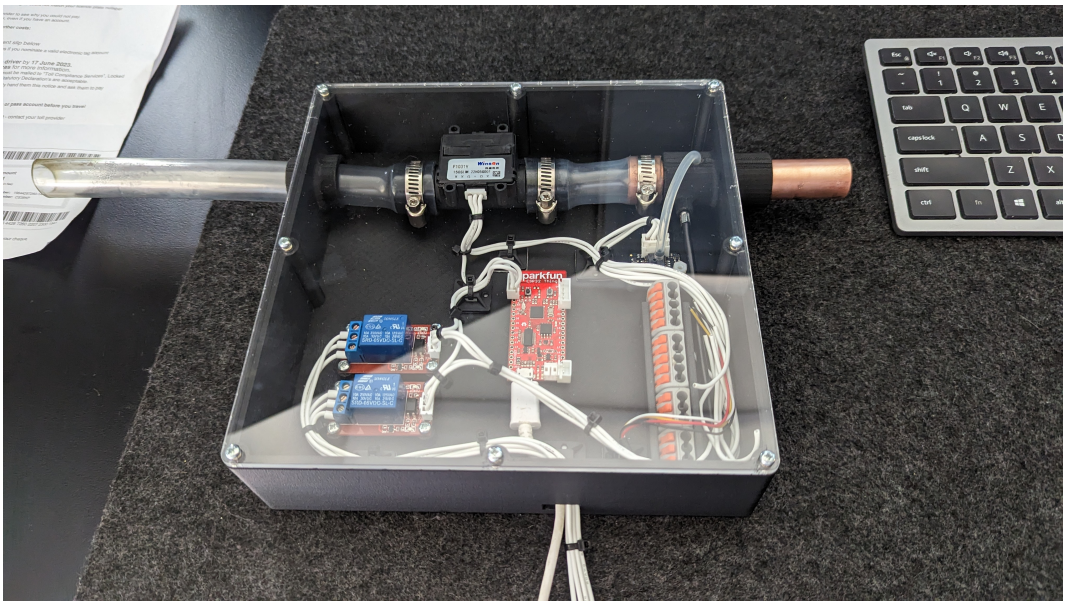

FIGURE 3.9: CO_2 sensing unit photograph. Photograph by the author (2024).

The final elements of the system are located at the top of the hydroponics enclosure, consisting of the control unit and the damper valve assembly. The control unit incorporates an ESP32 MCU connected to two 5V relay boards, which manage the operation of the damper valves. Additionally, an F1031V mass air flow sensor, and an SPD31 differential pressure sensor are integrated into the system. These sensors monitor CO_2 flow and detect any potential back-pressure issues that could indicate blockages or leaks, with automatic alerts configured to signal such anomalies.

Operationally, the control unit is synchronised with the hydroponics system's Raspberry Pi via WiFi. MQTT commands from the Raspberry Pi dictate CO_2 modulation within the enclosure. The master Raspberry Pi can initiate CO_2 ingress when enrichment is needed and divert CO_2 to the atmosphere when it is not, thus managing the internal CO_2 levels based on the hydroponic system's demand.

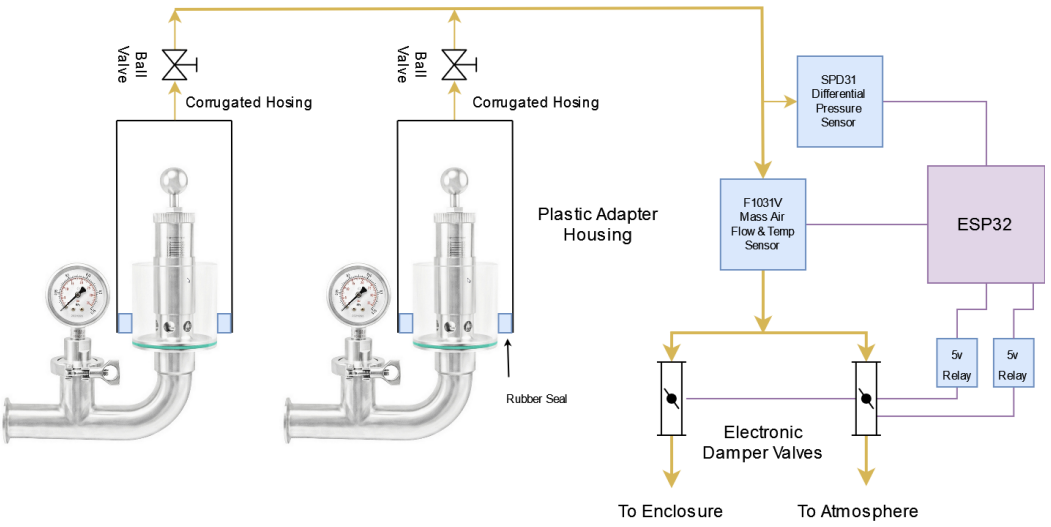

FIGURE 3.10: CO_2 sensing unit diagram.

3.9 Raw CO_2 Gas Chromatography

Given that the novel hydroponics system concept is utilising raw CO_2 recovered from the fermentation of beer it was considered crucial to analyse the constitution of the recovered gas in its unprocessed form to compare its properties to that of bottled CO_2. This was primarily in order to understand any potential phytotoxins or human health hazards that may be present.

In order to accomplish the required testing a specific apparatus had to be constructed to prepare the samples. The laboratory contacted indicated that the samples are typically stored in an aluminium pressure vessel which is delivered in a vacuumed state and sealed at both ends, before being filled by the client (using a pressurised CO_2 source).

In order to produce a sample from the fermenter it was required to pressurise the gas to 100 psi whilst also ensuring no contamination took place and the lines had been appropriately purged. To accomplish this a prototype sampling system was designed. Firstly, two ball valves on either end of the sample cylinder were installed and a Teflon piston air compressor was modified into the configuration detailed in Figure 3.11.

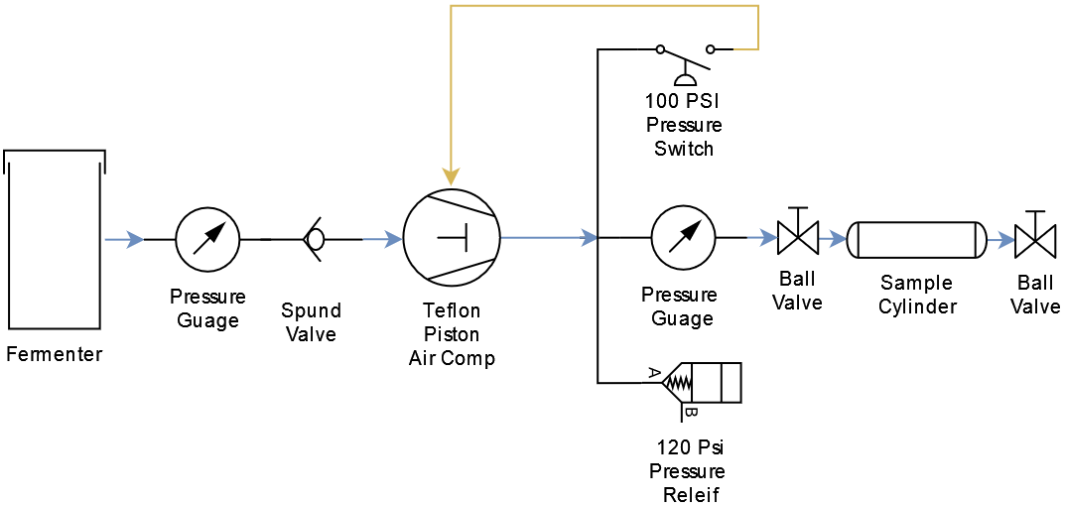

FIGURE 3.11: Fermenter CO_2 sampling system diagram.

There were several considerations from the breweries perspective with providing us with samples in this manner. Specifically, while the fermentation vessels are designed to hold moderate pressure they are not rated for any vacuum and when full of beer there is limited free airspace above. So it was important to ensure that at no point did the air compressor draw a vacuum on the fermentation vessel. To accomplish this the pressure gauge on the spunding valve was manually monitored and we ensured that it always read at least 1 psi during the sample extraction process.

Initially both valves on the sample canister were opened and the compressor was activated, allowing the CO_2 to flow through the vessel and purge any remaining oxygen. This was performed for approximately 30 seconds. At this point the end ball valve was closed pressurising the container. The air compressor turned off automatically due to the activation of the 100psi pressure switch, at which point the second ball valve on the cylinder was closed. Finally thread tape and brass end caps were applied to both the sample inlet and outlet to ensure no leakage occurred during transit.

To provide context for the sample obtained the specific details of the beer being produced are provided in Table 3.4. Due to the cost involved with testing it was not possible to run multiple samples across the brewing process which ideally would compare the similarity of gasses produced at the start midpoint and end of fermentation.

TABLE 3.4: Fermentation Specifications

Attribute	**Value**
Beer Type	Pale Ale
Yeast	*Saccharomyces cerevisiae*
Fermenter Type	8800 L Conical
Spunding Valve	Closed
Brewing Time	3 days
Temperature	18 °C
Starting Gravity	10.6
Current Gravity	9.1
Starting pH	5.2
Current pH	4.48

After receipt of the sample numerous tests were performed by ACS Laboratories located in Stubbs St Kensington Vic 3031.

The raw results of the CO_2 analysis are provided in Appendix C with the discussion of the gas composition detailed in Section 4.16 .

With all the elements above assembled and integrated in software the novel system was ready for initial commissioning. The next chapter details the results obtained from experiments and subsystem testing, as well as extended operation over 12 months. The analysis provides insights into the system's performance and the work conducted to fine-tune critical variables.

Chapter 4

Results and Discussion

Following the completion of the initial construction, the system commissioning process commenced. This entailed initial production of seedlings and first planting, as well as individual subsystem testing. In order to arrive at set points for some of the parameters detailed in subsection 2.3, a series of experiments were performed. After initial commissioning the system was operated for a period of 1 year which allowed for long term trends in the data to be considered and practical insights to be generated. The final resultant dataset contained over 100 million points.

4.1 PAR Experimentation

This section examines the photosynthetically active radiation (PAR) conditions within the system and evaluates how effectively light levels can be monitored and controlled using the IoT framework. This experimentation supports the research goal of determining whether a commercial-scale hydroponic setup within a brewery can be reliably managed through automated sensing and control (RQ1). The insights gained here also feed into the broader data capture objectives (RQ2), showing how real-time environmental feedback contributes to system optimisation.

The importance of precise and efficient lighting in hydroponics systems has been discussed earlier in subsection 3.5, with impacts on plant growth and resource use. The lights ultimately procured allow for dynamic adjustment of output using RS232 protocol. Upon installation and commissioning it was important to investigate the effects of varying the lighting software configuration and the results on PAR received by the plants. Recognising that light distribution is influenced by both the physical arrangement and the technological specifications of the lighting system, the goal was to determine the optimal software settings for this specific configuration.

Typical PAR information distributed by suppliers focus's on peak output or maximum capacity of the lighting for marketing purposes. We sought to determine if using the digital dimming functions of the lights we were able to tune the output to achieve ideal PAR values for the lettuce crop in the enclosure. The experiment comprised of manual measurements taken at the plant locations in a grid pattern. The PAR values were recorded using a Spot-On Quantum PAR meter with an advertised error rate of 1 µmol up to 6500 µmol, or +- 5%. Below are the results from analysing the PAR in the enclosure; readings obtained at the tested brightness settings, the row and column positions are as detailed in Figure 4.1 for reference with regards to the following figures.

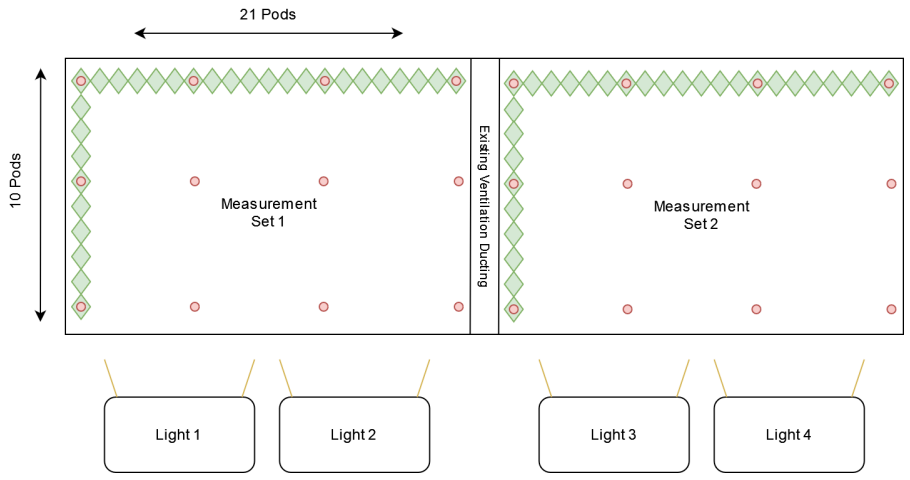

FIGURE 4.1: PAR measurement location diagram.

4.2 PAR Results - Raw

TABLE 4.1: PAR results table (umol/m^2/s) - brightness 20%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	18	30	34	36	23	34	35	25
5	40	106	92	60	58	93	116	35
10	15	31	26	23	24	27	34	14

TABLE 4.2: PAR results table (umol/m^2/s) - brightness 30%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	40	51	42	43	51	60	55	38
5	68	150	120	89	73	126	160	65
10	36	56	44	37	37	61	45	35

TABLE 4.3: PAR results table (umol/m^2/s) - brightness 40%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	45	66	61	67	52	75	66	36
5	83	185	145	113	85	153	174	82
10	50	62	58	51	36	51	54	40

TABLE 4.4: PAR results table (umol/m^2/s) - brightness 50%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	61	90	61	71	80	110	72	53
5	110	228	215	152	169	221	149	142
10	55	74	62	53	46	49	51	47

TABLE 4.5: PAR results table (umol/m^2/s) - brightness 60%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	60	91	96	99	76	110	92	69
5	102	226	256	156	131	185	176	115
10	53	93	88	75	56	60	85	56

TABLE 4.6: PAR results table (umol/m^2/s) - brightness 70%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	80	114	155	105	96	143	108	82
5	124	356	255	206	141	255	203	148
10	74	89	114	78	85	98	79	73

TABLE 4.7: PAR results table (umol/m^2/s) - brightness 80%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	95	156	121	97	108	172	165	113
5	165	376	220	216	161	325	315	198
10	76	150	162	99	98	106	130	82

TABLE 4.8: PAR results table (umol/m^2/s) - brightness 90%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	106	169	156	145	132	182	157	102
5	198	400	325	254	196	394	349	197
10	98	164	143	99	83	124	149	102

TABLE 4.9: PAR results table (umol/m^2/s) - brightness 100%

	Left Half Enclosure				Right Half Enclosure			
Pod X / Y	1	7	14	21	1	7	14	21
1	137	208	215	168	179	190	276	121
5	198	426	481	284	248	386	581	235
10	120	152	206	140	122	213	210	130

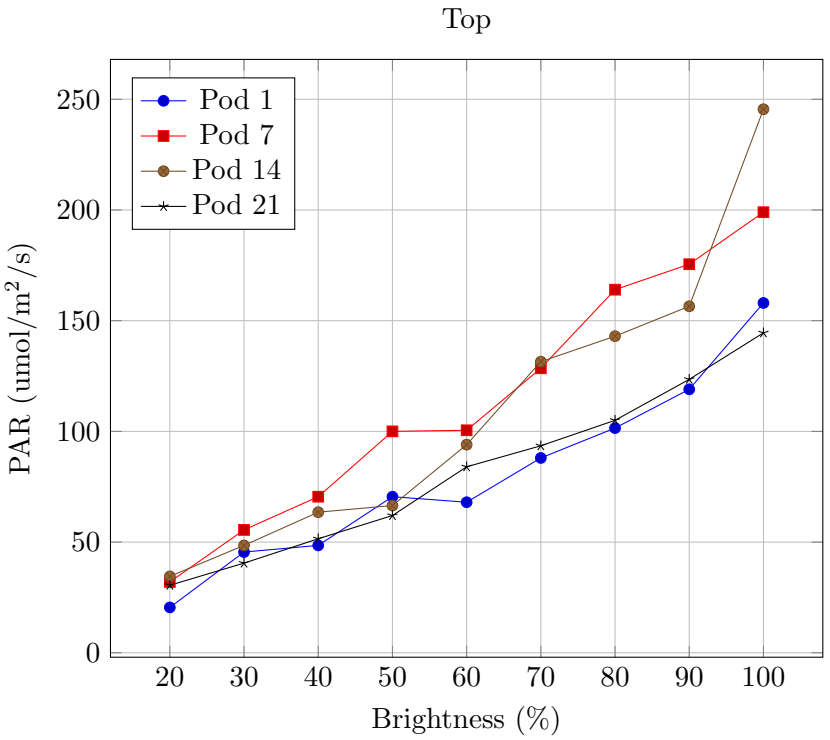

FIGURE 4.2: PAR results line plot - top third of enclosure.

4.3 PAR Results - Line Plot

To aid in analysis and find trends in the data line plots were produced, and are shown in Figure 4.2 to 4.4, which visualise the PAR values experienced by different individual plants (in the top middle and bottom rows) across brightness settings

Figure 4.1 (measurement diagram) displays the positioning of the lights in the enclosure, which are arranged horizontally co-linear. That is to say that the lights overlap horizontally and not vertically. The line plots below are labelled Top, Middle, and Bot, which indicate the vertical position in the enclosure (y axis), while the pod number indicates the horizontal position (x axis). The plots below are averaged across the two measurement sets.

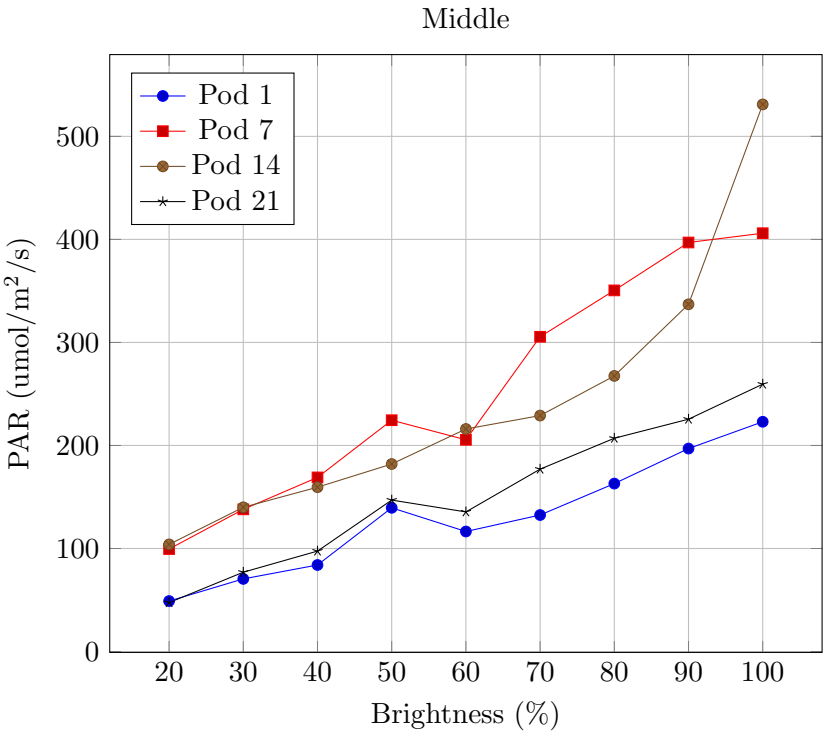

FIGURE 4.3: PAR results line plot - middle third of enclosure.

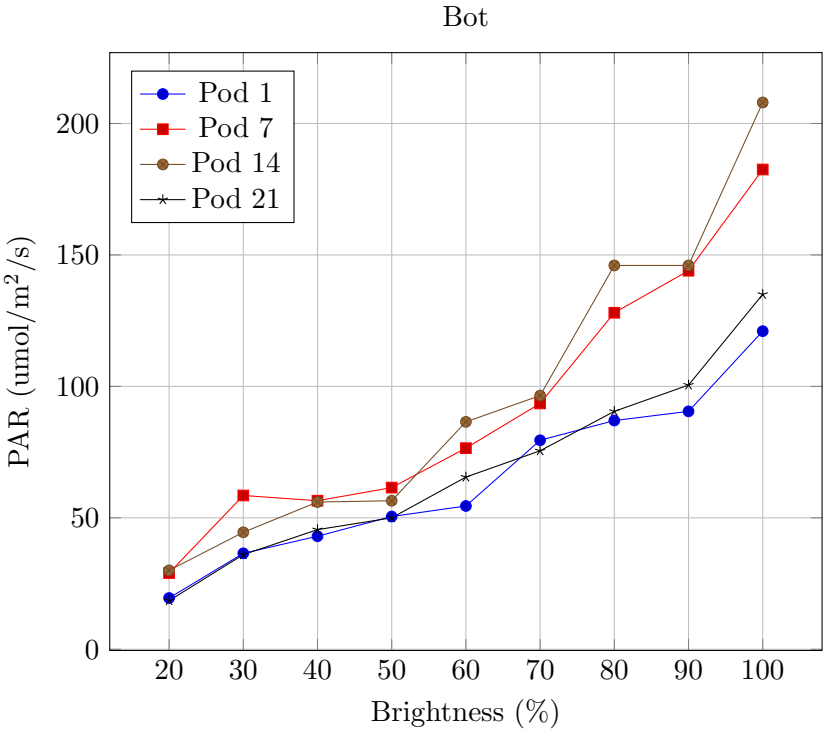

FIGURE 4.4: PAR results line plot - bottom third of enclosure.

4.4 PAR Results - Heat-map

In order to visually extract optimisations from the data, heat-maps were used and are displayed in Figure 4.5. The results are averaged across the two measurement sets and graphically convey the intensity of PAR using the recommended values for lettuce as the scale.

4.5 PAR Discussion

The findings reveal a notable deviation in light distribution among the pods, particularly between those positioned at the centre and the ends of our experimental setup. The disparities are not perfectly linear with regard to software changes and indicate inconsistencies in the expected output patterns: pods situated at the centre of the array experience more uniform PAR increments with increased brightness settings, while those at the ends exhibit reduced PAR scaling with brightness. This uneven distribution highlights some potential design flaws in typical hydroponics lighting setups which, while aiming to maximise light coverage, often neglect edge effects leading to sub optimal conditions at the peripheries of the cultivation area.

The line plots shown in Figure 4.2 to Figure 4.4 demonstrate the trends for different horizontally aligned pods with each colour demonstrating the results across the brightness settings 20-100 for an individual pot. In an ideal scenario there would be no deviation between the lines with all points occurring on top of each other. This would represent that the lighting setup scales perfectly, i.e as brightness values are changed each plant would receive the same increase in PAR. Interestingly, we see behaviour like this at brightness level 50% in Figure 4.4, but increasing to 60% causes separation again. Overall there is a coupling of the lines for pod 1 and 21, and similarly for pod 7 and 14. This demonstrates that the pods on the end of the wall receive less light as brightness is increased than the pods in the middle, which is logical given that the lights have some overlap in the middle and none on the ends.

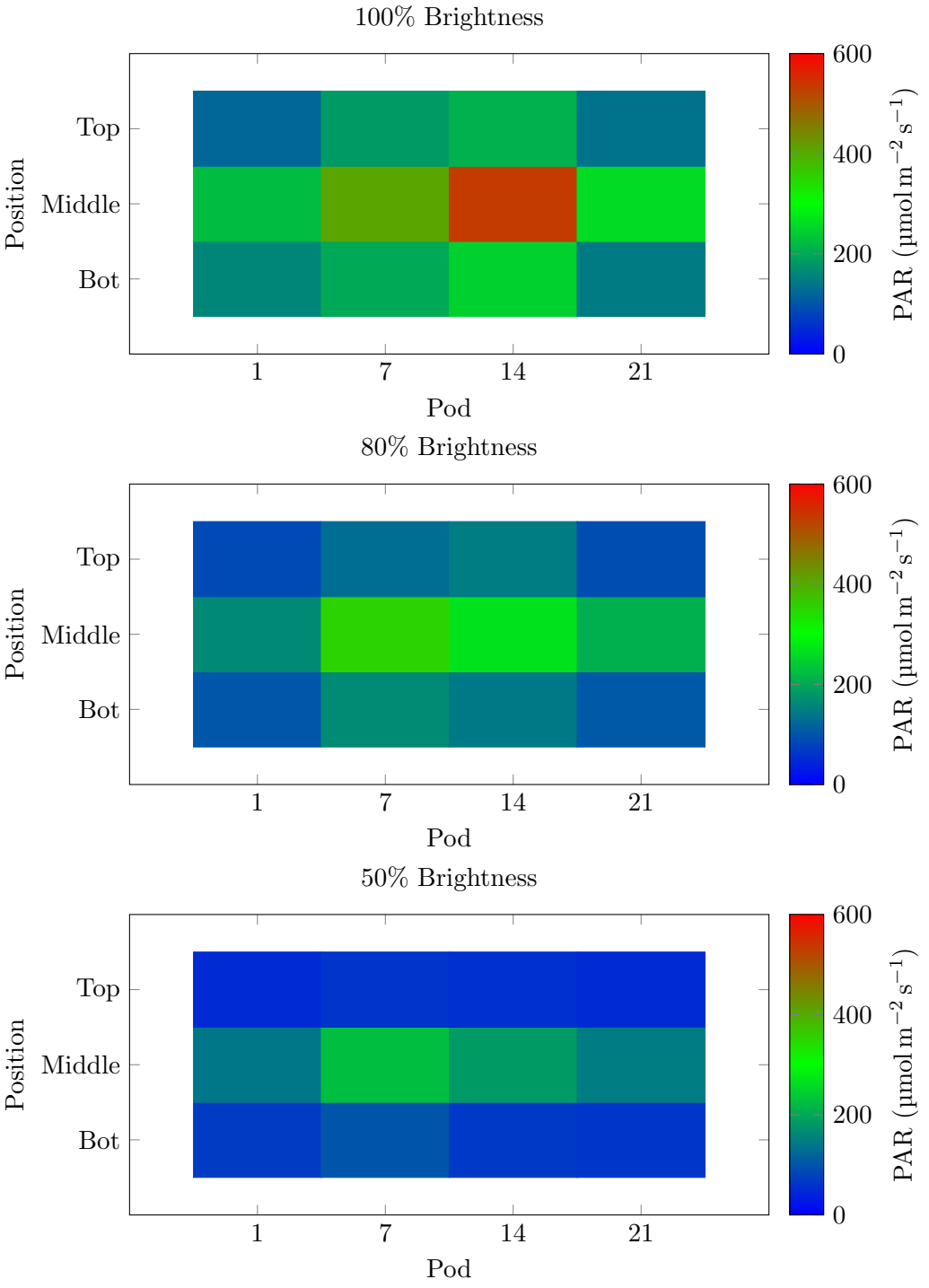

FIGURE 4.5: PAR results heatmap showing light intensity distribution across different pods and positions at various brightness settings.

In order to illuminate a vertical wall such as this there must obviously be 2 ends which will receive less light unless the setup is such that the lighting extends past the end of the wall which would be resource wasteful. The results clarify some interesting design points which can be considered by engineers and reveal that the data being provided by manufacturers is insufficient in most cases to completely optimise the design. The results are overly varied, for example moving from 30 to 40% brightness yields a 3% increase in overall range and from 40-50% results in a 29% increase in overall range.

There is a multitude of electrical variables which can influence the results in this type of experimentation:

- Dimming technology used.
- LED technology and output curve.
- LED Power supply design
- Number of LED's in light fixture.
- Length of lighting chain.

This information is provided by manufacturers, and occasionally also a PAR map, but detailed PAR trends and overlapping information and calculations are not. This really inhibits optimal design for the lighting system and relies on intuition and estimation. In this case the only design information available was the maximum output PAR which is most likely measured in the centre at the brightest point. From the offerings of commercial lights that we analysed marketing material for, the PAR information ranged from very little to some, but we could not find any detailed design documentation that would aid in this process. This is not to say that this information is not available on the higher end of the cost scale, i.e for very complex full farm scale lighting, but it was notably absent in the middle end of the market for a project of this size.

Looking at the data contained in the above figures holistically some trends emerge:

- As brightness is increasing light distribution becomes more inconsistent.

- Brightness increases are roughly linear overall, however some increases result in more PAR output than expected so one cannot rely on calculations to find the optimum software value.
- Heat maps showing distribution of PAR demonstrate that the overall spread of the lighting is far too focused which results in excessive PAR in the centre and insufficient PAR around the peripheries.
- The best software settings for the lights in this configuration require a compromise and cannot achieve a perfect PAR value for all plants.

The inability to obtain perfect PAR values for every pot stems largely from the fact the light sources used for this experiment produce a rectangular spread and the overlapping dynamics will always result in reduced peripheral PAR output unless extended past the canopy. While there exist lights which use a strip style configuration the problem still remains that perfectly overlapping them is a difficult undertaking practically, and is likely to result in similar situations of non optimal areas of light. The figure of 80% brightness was arrived at due to being the best compromise in this use case, as it provided the plants in the centre with slightly higher PAR exposure and the plants along the edges with a slightly low PAR exposure.

4.6 PAR Optimisation

Typical hydroponics systems use strings of LED lights arranged in some overlapping configuration to provide the most even spread of light possible and use spot checks to determine if values are within range. A truly optimised lighting arrangement would include a feedback loop to address each plants individual lighting needs. There does not appear to be any technical barrier to this existing, as addressable leds are commonplace in other industries. This could be implemented as a continuous grid of lights which are synced to a mobile PAR sensor. For example a worker could make checks and the lights adjust in real time to this feedback. It could be further automated using drone based sensors or mechanically moving sensors. As technology improves ideally lighting suppliers will be able to produce

products which are smaller and provide more granular control over the output overall. This would usher in a series of benefits for optimisation:

- Increasing the number of lighting nodes and control over each nodes output would allow for far better adjustment of PAR dynamically.
- Dynamic PAR tailoring would provide a more robust and consolable framework for adjusting the PAR over the course of the plants growth cycle.
- It would allow for mature plants and seedlings to be placed in close proximity to each other allowing for replacement of plants which are weak or dying in an already established crop.
- If a plant is showing signs of heat stress or has died it would allow for individual power off of the lighting node.
- It would reduce overall power consumption of the system by adjusting lighting spread dynamically for ambient light conditions, i.e if a window allows in full sun then the lighting could dim in the area around the window temporarily, and increase brightness if a cloud passed by.

In terms of this specific system and optimising this aspect, the data has revealed the most advantageous dimming values for the lettuce crop and conditions. However, this will only apply to this particular installation and can not provide generalised information which can be easily applied to other system designs. From investigating the information supplied by manufacturers and the real world results obtained through manual measurement and data analysis it is clear that there is significant room for improvement to current system designs. In an ideal scenario hydroponic lighting in the future would be able to be be configured using computer control and automation, thus would not require human intervention during periods of high ambient light, and adjusts for hot or cold spots over the canopy. Our results advocate for a more sophisticated approach to hydroponics lighting design, and suggest an avenue for future research be incorporating feedback mechanisms and addressable LEDs to dynamically adjust light distribution based on real-time PAR measurements.

4.7 Substrate Experimentation

In this section, various substrate options are tested to assess their suitability with the designed hydraulic system and plant layout, as well as the environmental conditions inside the brewery. The outcomes of these trials address practical design choices-such as scalability, water retention, and nutrient delivery, which underpin the feasibility of the system (RQ1).

Hydroponics is based on a soil free method of cultivating plants, and utilises nutrient-rich water solutions. The role of growth media, is to provide the plants with mechanical support and buffer nutrient retention. [82].

Given availability and recommendations we opted to test the following growth media types during our commissioning experiments to determine the most suitable type for continued operation:

Brand	**Product**
Canna	Hydroton Clay Pebbles
Grodan	Grow Wool Floc
Exfoliators Aus	Vermiculite Pearlite Mix 50%
Mixed	50% Grow Wool and 50% Clay Pebbles

TABLE 4.10: Table of substrate types tested.

In order to fix as many variable parameters as possible seedlings were produced through germination in the same filtered water. Once all seedlings had sprouted and produced leaves they were moved into the main enclosure. We aimed to plant 440 lettuce seedlings (all year round variety) completely filling all hexagonal pods. In actuality after vetting all of the seedlings for consistency this amount was not available, as some were of poor quality or did not germinate. The seedlings were all propagated under LED propagation lights in the same trays and consistent conditions. Out of 462 initial seedlings, 83 failed to propagate or were determined to be inconsistent with the overall quality, leaving 379 successful immature plants.

The seedlings were then distributed across the different growth media types randomly aiming to place 1/4 of the plants in each quadrant of the enclosure. Finally the doors

of the enclosure were closed and only briefly opened for inspections. Data was collected using the IOT system and remote monitoring of the experiment over the internet was performed using a WireGuard based mesh virtual private network. Parameters for the initial commissioning experiment were set to values obtained from literature:

Parameter	**Set point**
Internal Air Temperature	$22°C$
pH Set point	5.0
EC Set point	1400 $\mu S/cm$

TABLE 4.11: Environmental set points for substrate experiment.

The systems integrated cameras captured daily images for comparison which were sent offsite via WebDav protocol to a remote instance of NextCloud for observation and monitoring.

The method of seedling preparation described above became standard operating practice and was used in all future experiments.

4.8 Substrate Results

Figure 4.6 shows the before (day 0) and after (day 30) photographs for the growth cycle of the lettuce during the substrate experiment. Overall the different mediums all performed well and produced high quality lettuce. During the harvest of the lettuce detailed measurements on the condition size and weights of the plants were recorded. The raw results data for this experiment is contained in Appendix A.

FIGURE 4.6: Integrated camera start and end photographs.

The dataset comprises measurements of the plants grown in each substrate: Clayball, Vermiculite, Grow Wool, and Clay Ball Mix. For each substrate, the following parameters were recorded and are available in Appendix A:

- **Weight (g)**: The wet weight of the plant after removing any substrate material from the roots was recorded using a digital kitchen scale with accuracy listed as 0.1 g.
- **Length (mm)**: The length of the plant measured using a tape measure from the base to the top. The measurement was manually performed with the measurement recorded to the nearest mm.
- **Condition Commentary**: Observational comments on the plant's health or status using abbreviations. The legends for these abbreviations are as follows:

  UD Under Developed - Plant looked small compared its neighbours or general trend but otherwise healthy.

  EP Empty Pot - No plant was present in this pot.

  H Healthy - Healthy looking plant generally

  B Some Browning - Healthy plant with slightly browned leaf tips.

HD Healthy Double - 2 plants in the same pot caused by germination of more than one seed.

SB Some Burning - Plant appeared to receive too higher light exposure and appeared somewhat burnt.

VB Very Burned - Sickly plant that appeared very burnt.

4.9 Substrate Discussion

Overall, the various growth media demonstrated acceptable performance, generally yielding high-quality lettuce. During the harvesting of the first batch, detailed measurements of the plants' conditions, sizes, and weights were recorded.

Subsequent analysis of the harvest data resulted in the production of Figure 4.7 and Figure 4.8. These figures employ heat-maps to visualise the length and weight of the plants across each quarter of the enclosure. To address the presence of empty pods (EP), interpolated values were calculated using the average of all directly adjacent nodes. For any empty pod at position (i, j), its interpolated weight $w_{i,j}$ was calculated as:

$$w_{i,j} = \frac{\sum_{k,l \in N_{i,j}} w_{k,l}}{|N_{i,j}|} \tag{4.1}$$

where $N_{i,j}$ represents the set of all valid neighbouring positions that contain data, and $|N_{i,j}|$ is the number of such neighbours. A position is considered a neighbour if it shares an edge with the empty pod (not diagonally adjacent). For example, a pod in the middle of the grid would consider up to 4 neighbours, while a pod on the edge would consider up to 3 neighbours, and a corner pod up to 2 neighbours. This localised averaging approach was employed to preserve spatial trends in the data while providing visual clarity to the heat-map. There were a total of 77 empty pods in the dataset, out of a total capacity of 440 pods (i.e the enclosure was filled to 83% capacity). Specific locations of empty pods are available in Appendix A.

Overall this presentation offered a much clearer representation of the impact that different growth media have on plant development. Using the generated heat-maps also allows for the observation of distinct boundaries and trends between the various media more clearly.

Further examination of the raw data revealed that relying solely on the statistical elements of the dataset can easily lead to erroneous conclusions. For instance, looking at Figure 4.7 (length heat-map), which highlights longer plants in the Clayball section with yellow markings, might suggest that Clayball's are the superior growth medium. However, our first hand observations indicated that while plants in the Clayball section were indeed longer compared to those in vermiculite, they did not necessarily exhibit better health. Literature supports this observation, noting that elongated plant growth can occur as an adaptive response to nutrient scarcity [99] [100]. Therefore, we found it was important to integrate both quantitative and qualitative assessments when analysing the effectiveness of growth media.

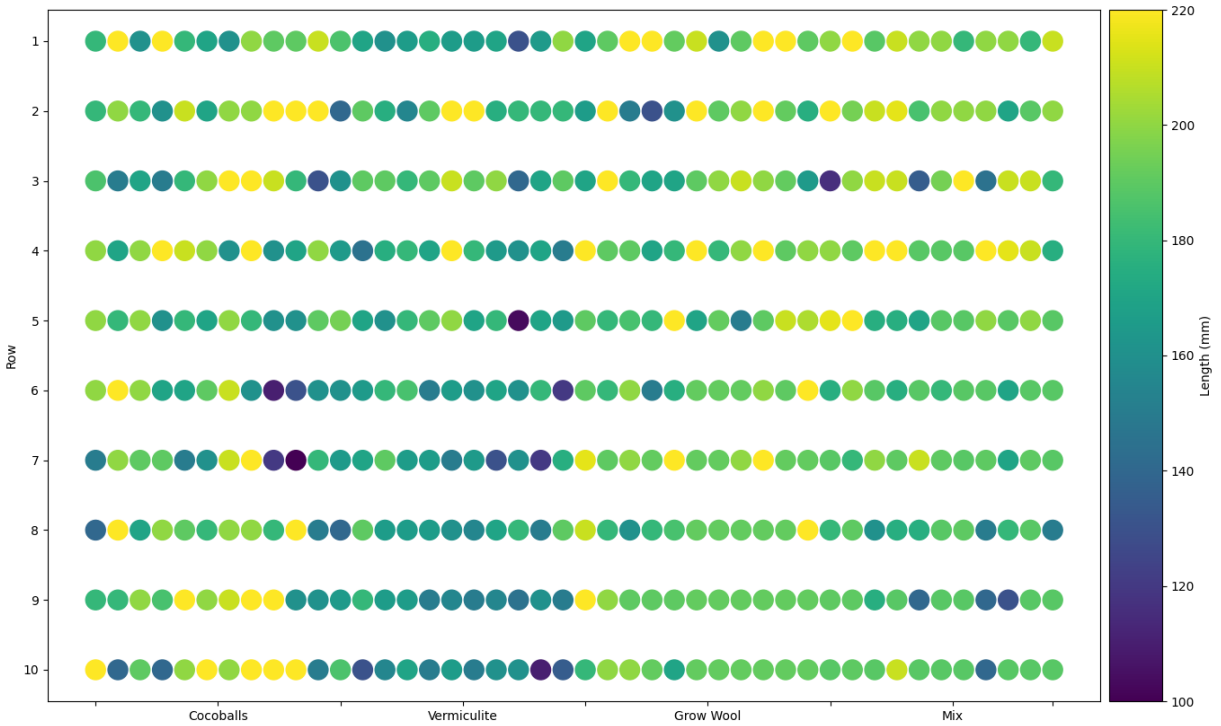

FIGURE 4.7: Substrate comparison heat-map - length (mm).

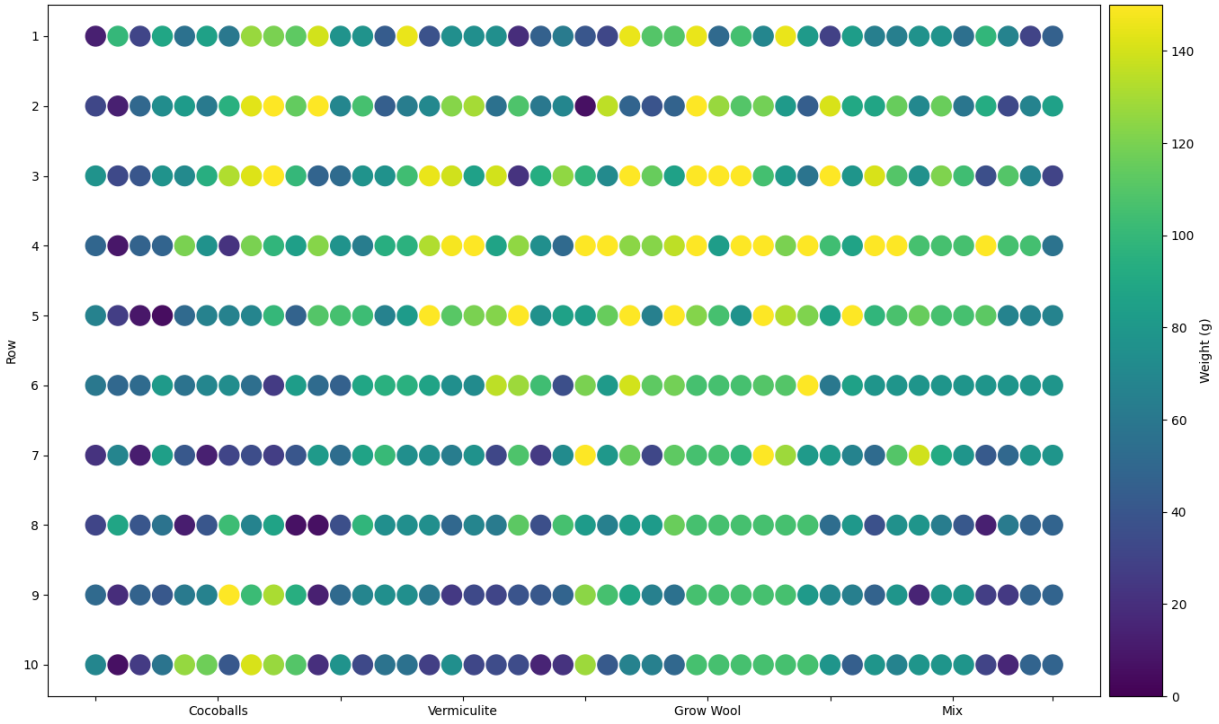

FIGURE 4.8: Substrate comparison heat-map - weight (g).

4.10 Substrate Optimisation

From analysis of the data and physical inspection of all the plants during harvest time the following conclusions were drawn regarding the choice of growth media for the enclosure. It was ultimately found that Grow Wool was the most performant substrate.

- Clayball produced quite long plants however they appeared the least visually appealing with long narrow leaves and the lowest average weight of 70.1 grams.
- Grow Wool produced the highest quantitative yield and most visually appealing plants and was clearly the superior choice for this application.
- Vermiculite (mixed with Perlite) performed the worst of the tested substrates with a low overall yield and the shortest leaf length.

- The Grow Wool Clayball mix performed quite well and had moderate length but a lower overall yield than the pure Grow Wool.
- Plants in the centre of the enclosure had burned tips and appeared affected by heat stress, with some of them dying.
- Plants at the bottom of the enclosure were generally smaller than those higher up, which was attributed to the distance from the source of the nutrient solution (at the top of the column).
- The exposed areas of the Grow Wool exhibited increased algae growth.

Table 4.12 below outlines the averaged data recorded from the plant harvest.

There were a number of potential sources of error in the experiment which we were not able to categorically exclude so are listed below:

- Effect of left and right edges of the enclosure receiving less light could affect the growth of those plants. However, this seems unlikely as vermiculite which was located in one of the middle sections performed poorly.
- The nutrient inlet to the dripper system in the enclosure enters on the right hand side of the enclosure and those closest to this entry point (grow wool and mix) may have received more nutrient solution than those closer to the end of the pipework, although this was not visually noticeable and we consider it unlikely to have had significant impact.

Overall the results obtained in this experiment demonstrate the clear effect that substrate choice has on hydroponic crops, and this is inline with findings in other literature [101] [102] [103]. It was observed that in this particular hydroponic configuration the substrate types which had the highest nutrient buffering effect where the best performers. The Grow Wool based substrates absorb a significant amount of nutrient and hold it very well. The clay balls for example which performed poorly appeared to dry out in places from the significant airflow present and did not remain entirely saturated.

The pot design, which was supplied by Vicinity Greenwall, relies on nutrient solution flowing between the vertically aligned pots through the effect of gravity. As such, there is not a significant spreading effect of the nutrient as it drips down from the pot above. Our results indicate that systems which rely on this effect require a substrate which has a natural wicking effect to draw moisture from the centre of the pot toward the edges and ensure the roots remain saturated. This is a potential area for improvement in the mechanical properties of the pot itself.

TABLE 4.12: Comparison table of plant growth metrics.

Metric	**Clay Balls**	**Vermiculite**	**Grow Wool**	**Mix**
Number of Plants	109	97	83	77
Total Yield (grams)	7646	7582	9109	6043
Average Weight (grams)	70.15	78.16	109.75	78.48
Average Length (mm)	185.96	166.22	191.51	189.04

Ultimately optimisation of this parameter involved selecting the most performant substrate from the available choices which in this case was pure Grow Wool. In a vertical growth context it appears that maintaining root saturation was the most important variable and the hydraulic design of pot and irrigation system must be considered to ensure the substrate is able to adequately wick nutrient to the entire root area without dry spots. This could also be achieved with an alternative pot design that creates a shallow well of nutrient at the base instead of being completely free draining as these were.

4.11 System Technical Performance

The headline aims of this study focus on introducing raw brewery CO_2 into an onsite hydroponic system in a confined urban footprint, both targets are predicated on the assumption that a tightly regulated micro-environment can be achieved and sustained. Introducing CO_2 into the system will inevitably cause changes to the multitude of data points being analysed thus it is critical that the stead state or baseline performance of the system is thoroughly analysed and optimised as far as practical to allow valid comparisons. Consequently, quantifying controller stability, latency, and failure modes constitutes an *enabling objective* that underpins **RQ 2** and **RQ 3**.

The process-control analysis that follows aims to address the following aspects of these questions:

- **RQ 2** probes what new insights can be gained when a fully-instrumented IoT system captures high-frequency, multi-channel data at scale. The 1 Hz sample rate gathered from 24 sensors and 11 actuators over twelve months forms the basis of the dataset explored in this chapter; converting those traces info performance indicators (KPIs) and evaluating accuracy and stability.
- **RQ 3** evaluates how *practically and efficiently* unprocessed brewery CO_2 can be utilised. Injection efficiency, production rate, and electronic control, are all functions of how accurately the automation system meters gas and attenuates overshoot.

4.11.1 Air Temperature

The enclosure contained 2 air temperature sensors and an ambient temperature sensor, shown in Figure 4.9 are the readings obtained over the first grow cycle averaged over 15 minute increments.

Considering the air temperature data provides some insights into environmental control within the hydroponic system. Temperature plots from sensors 1 and 2 in the enclosure (Figure 4.9) are initially aligned closely before the planting of seedlings. Post-planting,

a significant deviation between these sensors was observed, this issue was primarily attributed to the proximity of sensor 1 to the LED grow lights, which affected its readings due to heat emission. Manual verification was conducted, confirming the accuracy of sensor 2's measurements. This underscores the importance of sensor placement within the hydroponics enclosure to avoid data distortion by mechanical or electrical factors such as light and heat. Initially, it was assumed that two sensors would be sufficient given the small internal space. However, consistent findings revealed that the highly dynamic nature of the enclosure makes a sensor array significantly more practical overall. In general this finding applies to many of the sub-systems which often show variability depending on measurement location.

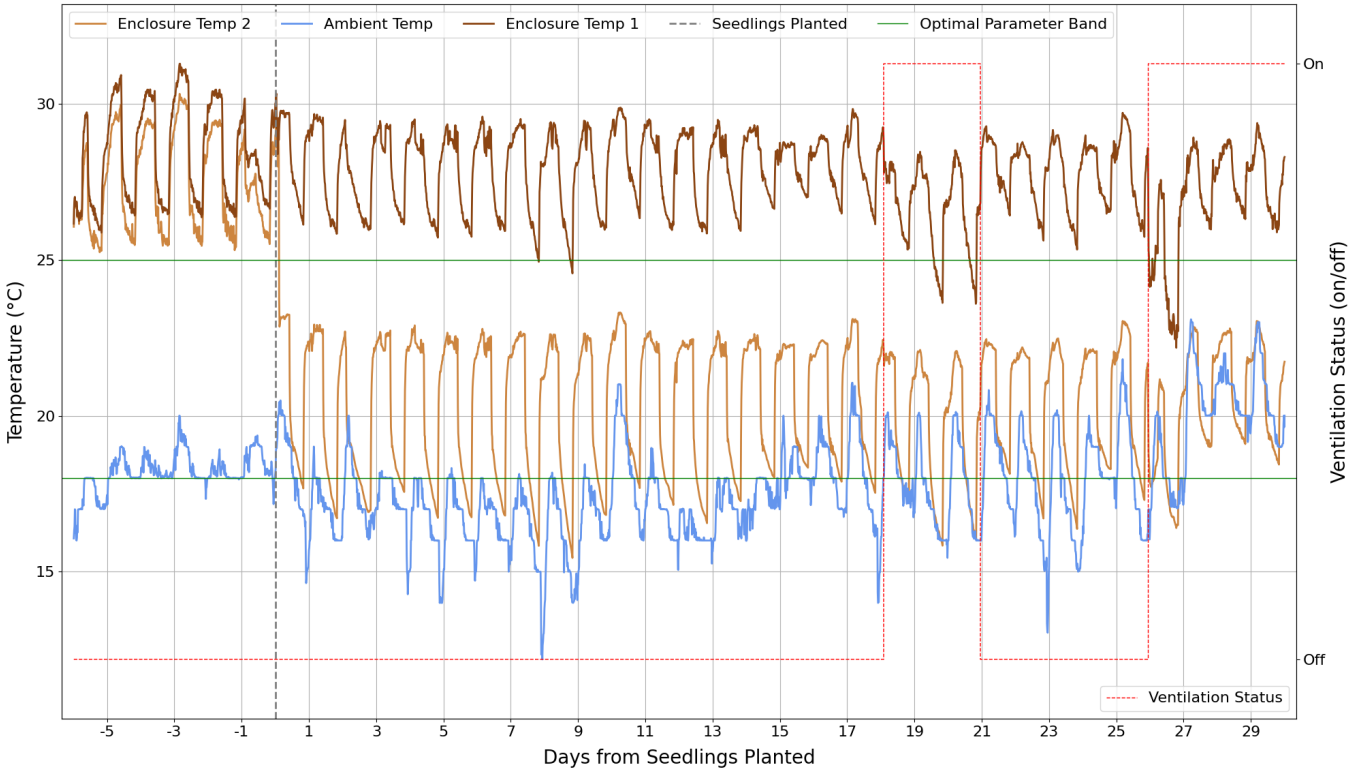

FIGURE 4.9: Parameter control graph - air temperature.

From day 0 to day 17, with the enclosure fully sealed, the temperature maintained a relatively stable daily oscillation between 17°C at night and 23°C during the day. This demonstrated the effectiveness of the air conditioning system (set-point 22°C) which moderated the internal temperature without exceeding this threshold significantly, in low ambient

temperature conditions. However, the operation of the thermostat on the system was such that when the lighting was shut off air conditioning would not change from cooling to heating mode, leading to a drop in nighttime temperatures with a minimum of 15.4°C, falling outside the optimum range for the crop.

The challenges of temperature regulation became apparent with the artificial lighting: without air conditioning, the average daily maximum internally reached 29.57°C, significantly above the ambient average of 20.0°C. Conversely, post-lighting, the internal temperature quickly matched the external, cooler conditions, dipping below our desired temperature range.

Introduction of ventilation between days 16 and 21 adjusted the temperature dynamics, reducing the overall daily temperature fluctuation to 4.34°C and elevating the nightly minimum ambient temperature. This adjustment illustrated the potential for passive climate control strategies to maintain day-time temperatures closer to ambient without mechanical cooling, while expecting a natural decline at night due to increased external airflow.

Given Australia's temperate to tropical climate and the objective of minimising operational costs and energy consumption, the initial decision was made to forgo the installation of a separate heating system. This approach proved effective under typical conditions; however, during unusually cold spells temperatures slightly deviated from the target range.

A proposed future enhancement involves integrating the currently external water reservoir within the air conditioned space or improving its insulation. By utilising the reservoir as a thermal battery, passive modulation of the internal air temperature could be achieved. A potential system would employ solenoid valves to direct flow through ambient or internal radiators for cooling or heating as required. Such an arrangement offers the potential to stabilise temperatures both day and night, while also harnessing solar energy during the day to reduce overall energy consumption.

In summary, findings demonstrate that while the current system efficiently manages temperature under moderate external conditions, integrating advanced thermal management

strategies could substantially enhance the control over environmental variables, allowing for further optimising crop production.

4.11.2 Humidity

Humidity control proved more difficult than initially anticipated, with the original design relying solely on the air-conditioning units air drying capabilities. Figure 4.10 displays the humidity data obtained during grow cycle 1. Analysis of the readings from sensors 1 and 2 initially revealed strong alignment prior to the planting of seedlings. As with temperature, a deviation in sensor readings emerged once the full system operations commenced, attributable to the proximity of one sensor to the lighting system. This exposure caused the surrounding air to become uncharacteristically dry, skewing the local sensor's humidity reading. Manual checks confirmed that sensor 2 provided a more accurate reflection of the overall enclosure's humidity,

Prior to the commencement of the experiment, the enclosed nature of the growing space naturally led to a slightly higher baseline humidity (43%) compared to the ambient external conditions (39%). This period included various tests of the electrical and hydraulic systems, introducing fluctuations expected before the official start of the experiment (day 0 in Figure 4.10).

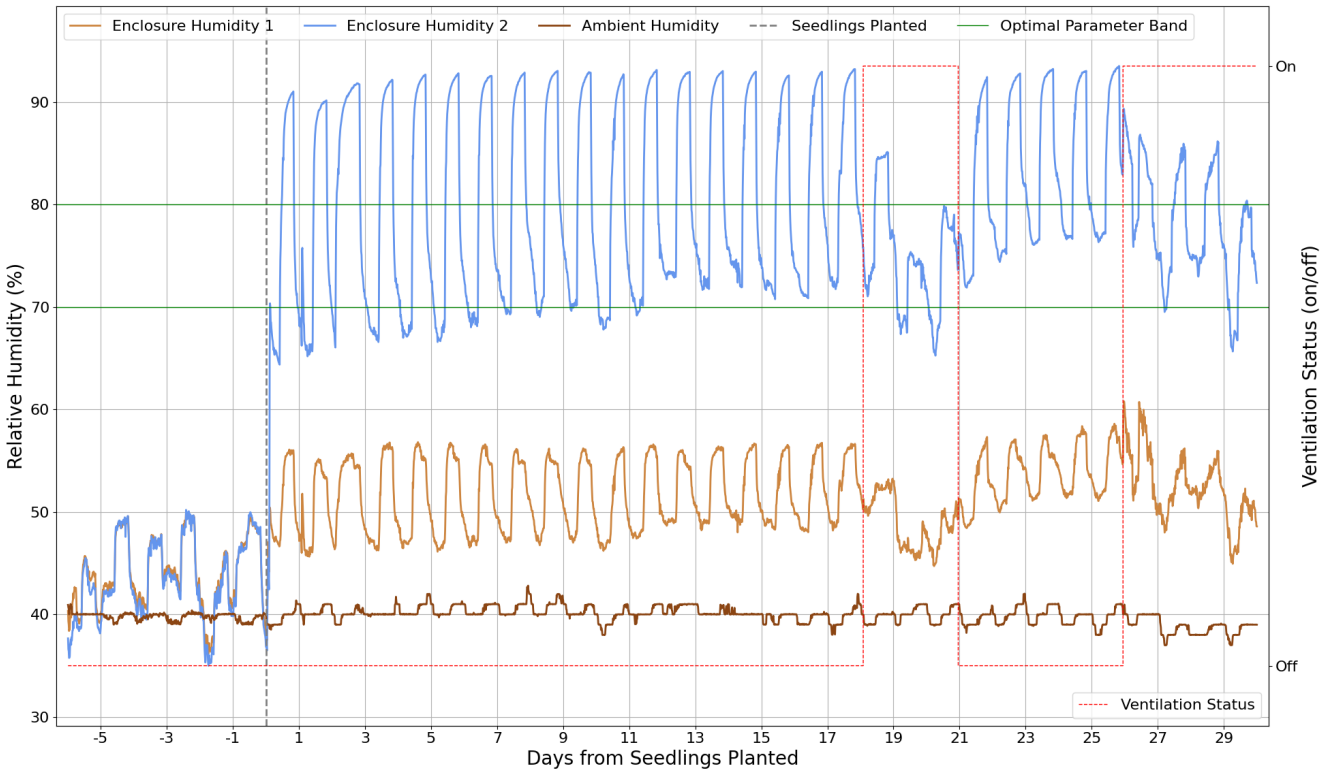

FIGURE 4.10: Parameter control graph - humidity.

Upon initiating the experiment, internal humidity levels rose to 70%, marking the upper limit of what the air conditioning system could regulate. A significant rise in humidity was noted overnight, exceeding 90%, this reflected the system's limits under dormant air conditioning conditions, which typically ceased dehumidification overnight as it entered power-saving mode. This resulted in pronounced nightly fluctuations, with peak humidity levels achieved overnight and the lowest during the day, influenced by the operation of artificial lighting and active air conditioning during the day which provided a downward pressure on humidity.

Before the implementation of external ventilation, we observed a consistent daily pattern, with an overnight humidity maximum averaging 93.1% and a daytime minimum of 69.3%. The uncontrolled high overnight humidity, due to the air conditioning entering power saving mode, necessitated further intervention post-experiment. A separate dehumidifier was installed, providing better control over moisture levels than the air conditioning system

alone, this was considered especially important for controlling algae growth which we experienced influenced by high overnight moisture conditions.

To maintain cleanliness and manage mould growth within the humid, indoor environment, utilising the dehumidifier to maintain relative humidity within the 60-70% range proved successful at limiting growth of algae and mould inside the enclosure. Though this range is slightly less than optimal for plant growth, it achieved a balanced compromise, significantly reducing contamination risks.

A future enhancement of the system could incorporate UVC or another form of air sterilisation technology to further mitigate the spread of mould spores and other pathogens within the controlled environment, as well as taking further steps to ensure the internal walls of the enclosure were perfectly flat and clad with a mould resistant finish.

4.11.3 Nutrient Temperature Control

Maintaining optimal nutrient temperature proved relatively straightforward, attributed primarily to its lower volatility due to the substantial volume of the water reservoir. The nutrient temperature data from grow cycle 1 is contained in Figure 4.11. A simple aquarium heater set to 21°C was able to consistently maintain the nutrient temperature with a daily average of 21.27°C and a minimal daily fluctuation of only 0.13°C prior to the commencement of the experiment.

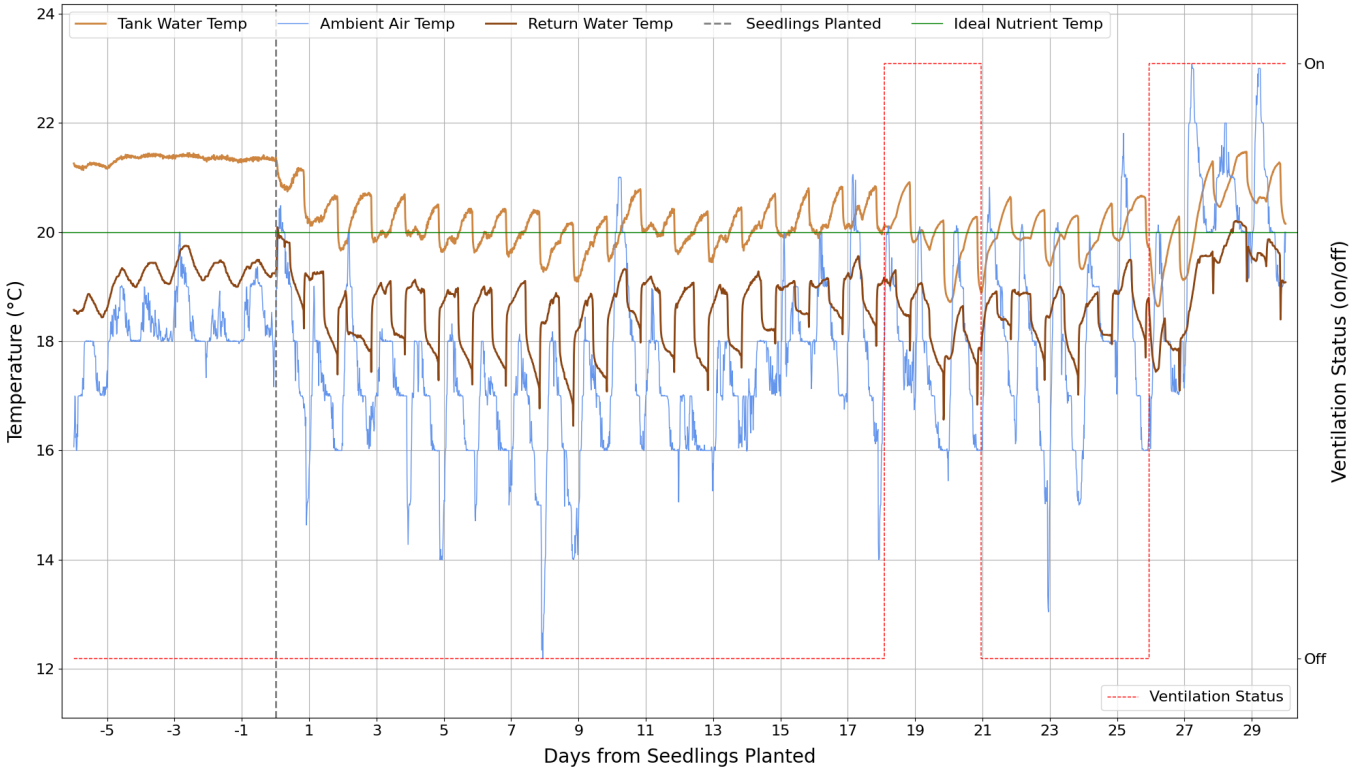

FIGURE 4.11: Parameter control graph - nutrient temperature.

Following the analysis of temperature and humidity, it was observed that all key system metrics were closely intertwined. Post-initiation (after day 0), the daytime water temperature began to decrease, indicating that the heating element was insufficient to compensate for the heat loss as the nutrient solution circulated through the enclosure. Despite this, the nutrient temperature within the tank maintained a stable range, averaging 20.1°C with a nightly fluctuation of 0.9°C. The nutrient temperature oscillated effectively around the optimal value of 20°C, fluctuating by only 1°C, which was a pleasing outcome.

A key observation from our analysis was the notable disparity in return water temperatures. The temperature at the drainage exit point (the return temperature) showed significant heat loss during transit through the PVC pipes and plant pots, with a daily average of 18.5°C and a larger range of 1.56°C. While it is logical to expect some heat loss as the nutrient solution travels to the plant pots, our review of existing systems revealed that it is uncommon to measure temperature directly at the point where plants receive the nutrients; typically, only the tank temperature is monitored.

Given the specifics of the system, such as the material of the pipework (e.g., copper or plastic) and the routing and length of the plumbing, these factors could lead to significant discrepancies in measured temperatures. Although tank temperature is undoubtedly critical, our findings suggest that it would be prudent to also monitor the temperature of the solution at the root zone—both incoming and outgoing. Future system designs could include a new measurement and tracking point for root zone temperature. Ideally, a feedback loop for the tank temperature would optimise around the averaged nutrient temperature values between the first and last pots, ensuring that all plants receive the correct temperature nutrient solution and accounting for any losses through the plumbing system.

4.11.4 Nutrient Quality Control

The first five days of grow cycle 1 involved trialling different aspects of the system, such as automatic pH control and nutrient delivery via the peristaltic pumps. The Node-RED-based controller functioned effectively during initial tests, it was deployed using a simple conditional control algorithm. The algorithm utilised a series of nodes to filter and measure data from the Atlas Scientific probes and employed conditional logic to dispense nutrients, incorporating timers to allow system stabilisation post-dosing. These dosing events were recorded into the Influx database and are visually represented in Figure 4.12 by red lines.

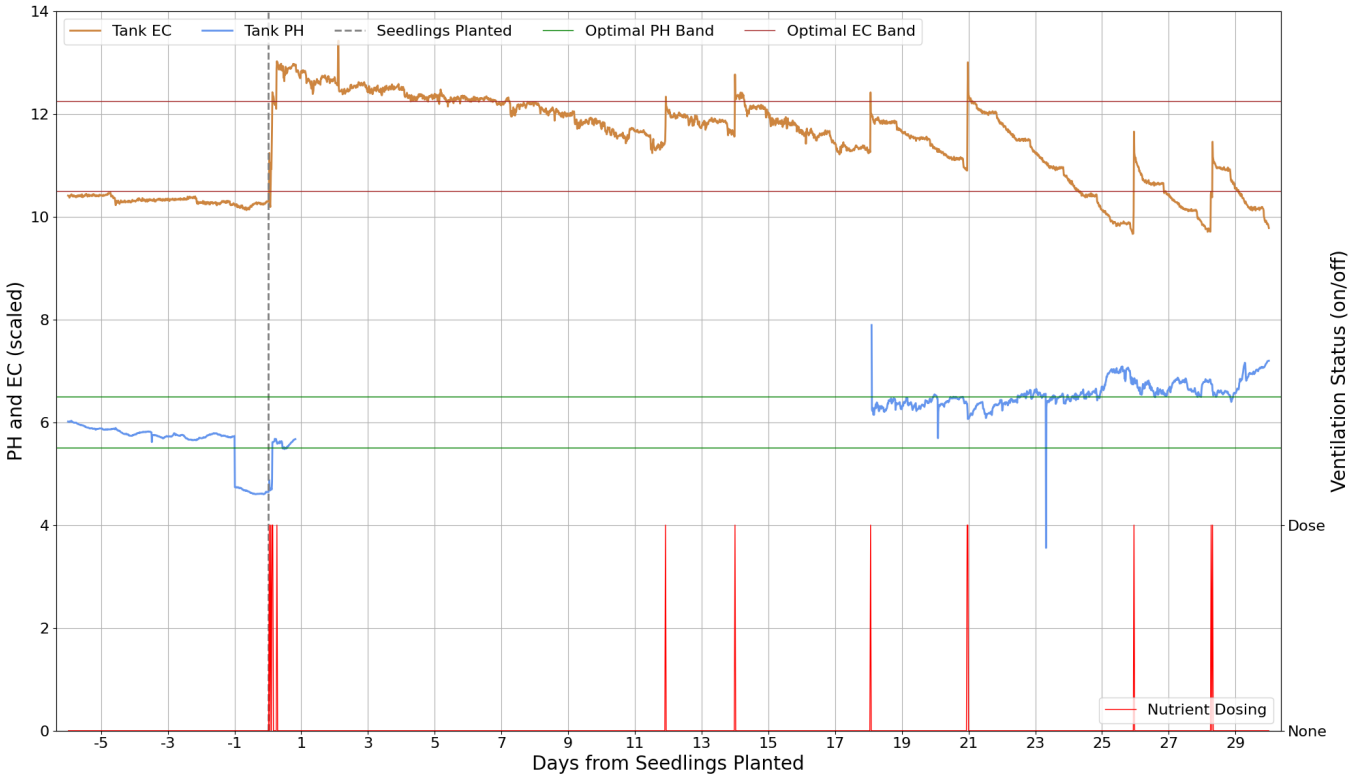

FIGURE 4.12: Parameter control graph - nutrient concentration.

Setup of the system post cleaning or flushing quickly revealed that achieving the correct initial water chemistry was a time-intensive process, requiring extensive trial and error with manual adjustments using pH-modifying agents. The specific agents used were sodium hydroxide for pH up, and phosphoric acid for pH down. Initially, the pH started on the lower end of the acceptable range, averaging 5.75 on the first day. Unfortunately, an installation error on the following day resulted in water damage to the pH probe connections, resulting in sensor failure; this was rectified on day 18, as indicated by the blue line in Figure 4.12. During the period of sensor outage, manual measurements and pH adjustments were made. Typically, the pH registered high after each nutrient addition, necessitating repeated applications of phosphoric acid to stabilise it within the target range.

Nutrient concentration, indicated by Electrical Conductivity (EC), was adjusted for display in Figure 4.12 using min-max normalisation:

$$\text{scaled}_{\text{EC}} = \frac{14 \times (\text{value} - 0)}{1600}$$

On the first day, the EC was approximately 1500 μS/cm, above the optimal range due to manual overdosing during the initial manual chemistry setting. Instead of discarding the 200L of nutrient solution, we allowed the EC levels to gradually decrease back within the desired range.

While the conditional control in the software performed adequately, it was susceptible to data spikes immediately following injection events. These spikes represented significant surges in nutrient concentration as the chemicals mixed within the main reservoir. We tested several mitigation strategies, including software control locks in Node-RED and dosing into an intermediate tank which slowly mixed into the main tank. A dosing supervisor feature was implemented to monitor dosing events over the past 24 hours and set an upper limit on dosing, which would trigger a system lock if the threshold was exceeded. Unfortunately, this feature led to the system inadvertently locking on day 21 when a spike surpassed this threshold. Due to the user interface not being updated to reflect the new lock feature, we did not realise the system had locked, resulting in a gradual decline in EC until manual intervention was necessary on days 21-26.

With hindsight, we developed more sophisticated conditional control strategies for future operations. We established an averaging system to smooth out data inconsistencies by averaging measurements over the last 10 readings. Additionally, a timer loop required that the average of these readings exceed the set threshold for a specified duration before dosing would occur, effectively reducing the impact of outliers. These control aspects and code can be found and used in the linked github repository [104] inside the pH Control flow.

Despite the success of similar systems on a smaller scale, we encountered issues when scaling up to a 200L nutrient reservoir. Smaller dosing events were too minor to affect the measurements significantly enough to detect outside of the sensor noise requiring larger dosing events. We adjusted the system to increase dosing amounts incrementally by approximately 100 μS/cm, ensuring detectable changes beyond the sensor noise thresholds.

However, the dynamic nature of EC depletion, which increased as the plants matured, necessitated further adjustments to the logic to prevent repeated lock-ups.

Academic literature was consulted to explore solutions like machine learning and fuzzy logic for more effective handling of dosing dynamics. Although these methods showed potential in enhancing dosing accuracy, the most challenging aspects of nutrient quality control emerged from unforeseen events not accounted for in the original logic, such as sensor maintenance or system reboots due to power outages. Such instances necessitated manual interventions, occasionally resulting in deviations from optimal nutrient levels.

In conclusion, while the automatic dosing system functioned autonomously for a substantial portion of the operational period, our improvements moving forward would focus on better handling of edge cases such as tank draining and refilling. Incorporating data-driven approaches to predict and manage these events would significantly enhance the system's automation potential and overall reliability as we seek to remove any human error from the process flow.

4.11.5 CO_2 / Air Quality Control (non enriched)

Initial assessments of CO_2 levels in the brewery environment, which hosted the hydroponic enclosure, revealed fluctuating ambient CO_2 concentrations due to brewery operations such as CO_2 tank refills, fermenter purging, and bottling activities. Typical ambient readings showed a daytime average of 623 ppm and a nightly minimum around 398 ppm, with occasional spikes up to 1500 ppm. The upper limit on these daily spikes was variable and 1500 ppm was a conservative upper average, however this still represents a significant increase over atmospheric normal by a factor of at least 3.

Upon sealing the enclosure and the beginning of grow cycle 1 (Figure 4.13), we observed a stabilisation of CO_2 levels with an average of 456 ppm, aligning more closely with atmospheric norms; detailed statistics are provided for reference in Table B.1 to Table B.5 in Appendix B. Activating ventilation led to dynamics resembling pre-experimental conditions, with no dips below atmospheric norms and higher daily spikes. However, the most notable observations were made during the period when the ventilation was

deactivated and the plants had matured, specifically from day 21 to 25. During this phase, we recorded a significant daily fluctuation in CO_2 levels, with day-time values dropping to as low as 133 ppm, significantly below the atmospheric average, and even lower again below the direct ambient CO_2 levels in the brewery. Conversely during the night time we saw rises in CO_2 internally from well below to double atmospheric levels or around 800 ppm. We attribute the night time CO_2 rises to the plants transitioning from photosynthesis to solely respiration.

Later data analysis led us to consider Alexandra's findings which discuss the complex interactions between plant respiration, photosynthesis, and environmental CO_2 levels. His study indicates that under elevated CO_2 conditions, both daytime and nighttime plant respiration rates are reduced, suggesting a conservation of carbon during respiration. [105].

The opposite effect was observed when subjecting the plants to incredibly low atmospheric CO_2 levels during the day, resulting in significant CO_2 generation (from respiration) during the night time when in a sealed environment. This is an interesting finding which warrants further investigation and opens an avenue for cross discipline collaboration. We cannot completely rule out outside CO_2 ingress however during construction extensive measures were taken to prevent this as detailed in Section 3.3.

To observe the effects of opening the enclosure door on CO_2 levels, a simple optical switch was later added to the system, with its connection integrated into the Influx database for real-time data collection and analysis. The results from grow cycle 2 are similar to grow cycle 1, however this time ventilation was not activated and instead the door was opened to allow CO_2 entry. These results are displayed in Figure 4.14, and provide a similar characteristic daily fluctuation of well below normal to well above normal CO_2 levels.

The most interesting effects observed are shown between day 10 and 14 where a consistent pattern of CO_2 peak and trough declining day by day can be identified. Measurement of the CO_2 absorption of plants is very difficult to accurately calculate but the data showed a relatively linear depletion of 100.01 ppm per day during this period. Looking at the recovery to system stability after door opening events we can see a very sharp increase when the door is opened followed by quite steep decline to prior levels once the door is closed. The rate of decline was variable but it appeared to take approximately half a

daytime cycle to return to prior levels. Looking at day 17 it can be seen that if the door is opened close to the end of the daytime photo-period, there is no return at all with CO_2 levels continuing to rise once the lights are shut off.

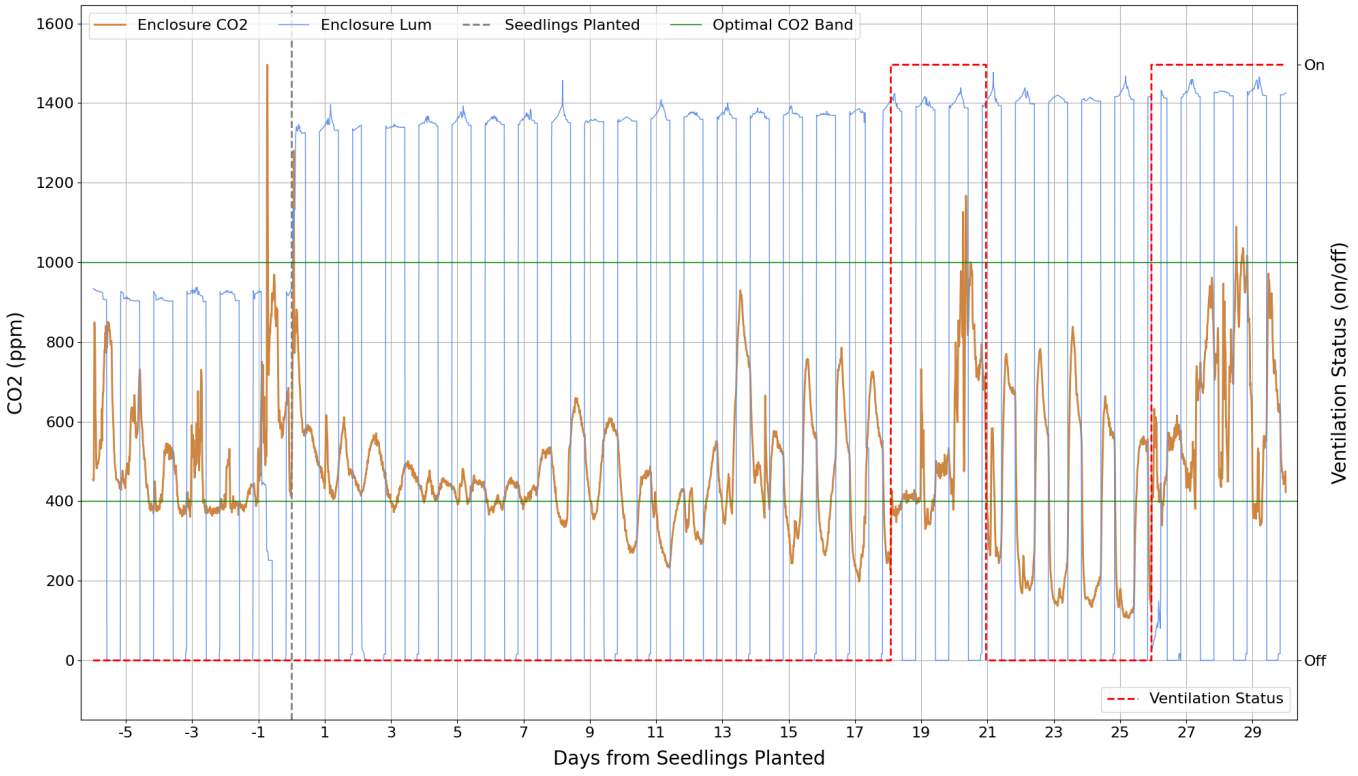

FIGURE 4.13: Parameter control graph - carbon dioxide concentration 1.

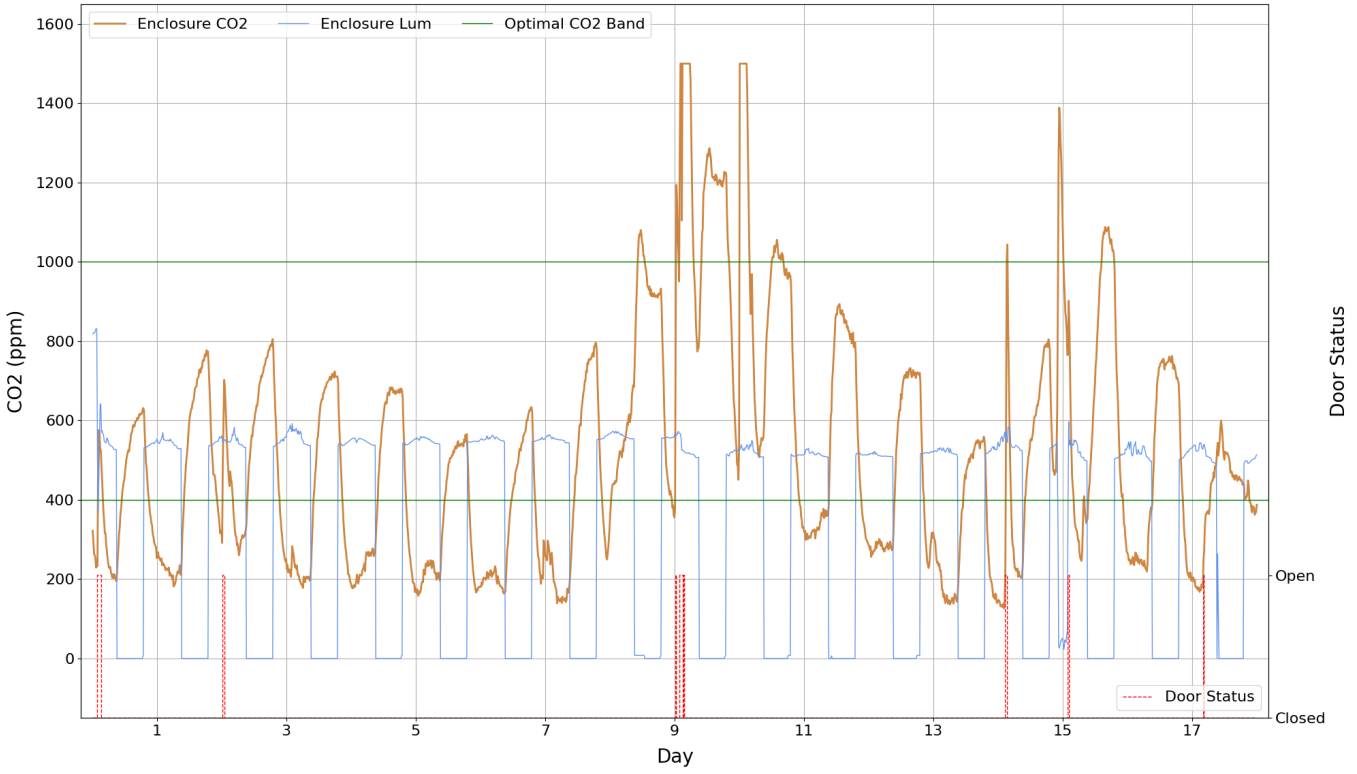

FIGURE 4.14: Parameter control graph - carbon dioxide concentration 2.

4.12 System Technical Performance Discussion

This section investigated the system technical performance through analysing the data collected on each subsystem. The IOT derived system effectively controlled environmental factors crucial for plant growth but there was also room for improvement in many aspects. The system maintained optimal conditions for lettuce growth but was unable to accommodate all edge cases and variations which it faced. The system demonstrated the viability of IOT technology in enhancing the efficiency of vertical farming inline with existing literature [16–18], but also identified some of the issues associated with scaling to this size which require further work.

As detailed by Despommier [4], this method of modern agriculture fosters the cultivation of crops in vertically stacked layers within controlled indoor environments. It relies on nutrient-rich water solutions and inert stabilisation medium instead of traditional soil. The benefits encompass increased yield per square meter, substantial water savings, and the ability to grow crops year-round and in any climactic conditions.

Ray [8] explored the use of different IOT architectures to reveal how these systems, while vast, can be tailored to the unique requirements of various sectors. If the growing conditions for farming can be optimised through IOT technology, it would represent a significant advancement in agricultural efficiency.

The combination of automation, remote monitoring, and data derived decision-making in hydroponics represents a fundamental shift towards achieving optimal crop yields while minimising resource usage [15].

When optimised plants can effectively uptake essential nutrients, as both nutrient solubility and root metabolic activity are optimised in the temperature range of 14°C to 25°C depending on plant species [56, 83–85].

On the other end of the spectrum, excessively warm nutrient solutions can be equally detrimental. Elevated temperatures can reduce the solubility of oxygen in water, potentially leading to root stress and exacerbate vulnerabilities to root pathogens [87].

The system required regular maintenance with regard to algae growth [88].

The substrate types provide mechanical support and buffer nutrient retention [82].

Root plasticity is an adaptive response to nutrient scarcity [99, 100]. Therefore, we found it was important to integrate both quantitative and qualitative assessments when analysing the effectiveness of growth media.

The results were inline with findings in other literature [101–103]. It was observed that in this particular hydroponic configuration the substrate types which had the highest nutrient buffering effect where the best performers. The Grow Wool based substrates absorb a significant amount of nutrient and hold it very well. The clay balls for example which performed poorly appeared to dry out in places from the significant airflow present and did not remain entirely saturated.

The pot design, which was supplied by Vicinity Greenwall, relies on nutrient solution flowing between the vertically aligned pots through the effect of gravity. As such, there is not a significant spreading effect of the nutrient as it drips down from the pot above. Our results indicate that systems which rely on this effect require a substrate which has a natural wicking effect to draw moisture from the centre of the pot toward the edges and ensure the roots remain saturated. This is a potential area for improvement in the mechanical properties of the pot itself.

The facility uses a commercial grade carbon capture system to purify and bottle the CO_2 before delivering it in tanks [76].

Unforeseen events such as power outages, pest infestations, and algae growth in the nutrient reservoir posed challenged and risks to crop health. They highlighted the need for more robust contingency planning when designing the software and hardware systems.

The need for more expansive sensor systems was identified when being used at this scale. Current typical methodologies such as monitoring the nutrient reservoir temperature do not account for losses caused by pipework and cause a deviation from optimal conditions. Similarly the dimmable lights that were used were able to be tuned to a local optimum but for a truly optimised system in this scale the lighting would need to consist of a matrix of smaller light elements with a feedback loop.

From a data analysis perspective it was necessary to overlay status data visually or statistically on variables of interest to analyse it. It would be prudent in future experiments to include dynamic tagging of data based on system events. For example, all temperature data having the tag door open would make it significantly easier to understand changes in the internal temperature and quickly realise that an inflexion point is due to this tag changing.

The importance of categorising system states became apparent and this has not been widely discussed in current literature reviewed as the experiments were mostly on a smaller scale. At this larger scale it is critical to be able to quickly ascertain the system state when making automated decisions based on the incoming data stream. For example, an alert system to prompt the user with a classified info, warning, error was developed and setup however events such as opening the door cause this to trigger, and resulted in extra conditional logic. The conditional logic quickly became a slippery and complicated slope with many different conditions being placed on events all around the system. It would be far more beneficial to spend the time to distinguish external inputs and map a table of system states so that all logic and analysis can be set to predefined conditions. For example, if the system state is active maintenance then the pH probe may be calibrated during this state so the system should ignore the data received from it during this period and pause automation's until the state is changed back to run. During the initial design some of these edge cases were not anticipated and while there were functions available such as manual mode, if an operator error occurred it could lead to a series of cascading unintended automation's triggering. There is a need for more focus on a strategic and well defined framework for hydroponic system operation using IOT so that multiple sensors and automation's can be combined without leading to conflicting behaviour.

The extensive dataset collected has provided valuable insights into the interplay between different variables and their impact on the overall system. The natural coupling of so many of the variables in the system dataset can make significant challenges when drawing conclusions, however this level of data collection sets a foundation for further optimisation of hydroponic systems. Generally speaking, further research is needed to explore the scalability of IOT-enabled hydroponic systems, particularly in larger urban farming setups.

4.13 Analysis of Fermentation CO_2 Introduction

This section analyses the introduction of raw, unprocessed brewery into the hydroponic environment. The findings here directly address the third research question by testing the practical and efficient use of brewery CO_2 without energy-intensive processing. At the same time, the analysis demonstrates how integration with the IoT control system allows dynamic adjustment and tracking of enrichment levels (RQ2)

Upon completion of the initial system commissioning and the first growth cycle (detailed above), attention was moved to activation of the novel direct use CO_2 subsystem. Upon first activation the harvester was configured with the atmosphere damper valve open and enclosure inlet valve closed. It was decided to collect a few days data allowing the CO_2 to vent straight to atmosphere as a baseline. At this point the damper valves positions were reversed allowing the fermentation CO_2 to flow directly into the enclosure.

Figure 4.15 illustrates the flow rate of CO_2 through the harvester into the hydroponics enclosure and captures the dynamic nature of both the supply and absorption involved in this concept. Initially, upon harvester connection at day 0, CO_2 production commenced with the output being diverted to the atmosphere. During the first three days, the enclosure CO_2 levels displayed a typical pattern—an oscillating decline, with nightly peaks due to plant respiration, and daytime troughs dipping well below atmospheric norms.

On day 3 the CO_2 vent was electronically opened, allowing direct CO_2 flow from the fermenter into the hydroponics enclosure. This resulted in a rapid spike in CO_2 concentration, reaching up to 1000 ppm, before declining back to approximately 300 ppm over the course of the day. Intriguingly, over the subsequent days, the timing of the CO_2 highs and lows shifted progressively earlier, ultimately inverting the pattern whereby peak CO_2 levels occurred during daytime rather than at night, stabilising in this pattern for several days.

Upon establishing a steady state, the CO_2 supply was increased, This adjustment caused a surge in internal CO_2 levels, peaking at over 5000 ppm, followed by considerable variability throughout the day. This phase highlighted the challenges in tuning the system given the variability in CO_2 generation and absorption.

To address the fluctuations observed and achieve more stable CO_2 levels within the enclosure, we concluded that a buffering mechanism would be necessary in future harvester designs. This would modulate the CO_2 supply against plant consumption rates and make stable electronic control easier.

Harvesting CO_2 directly from the brewery's fermenters proved successful in elevating internal enclosure CO_2 levels, thereby mitigating the daytime lows previously observed. However, also underscored the challenges in achieving truly autonomous control over the variable CO_2 supply directly.

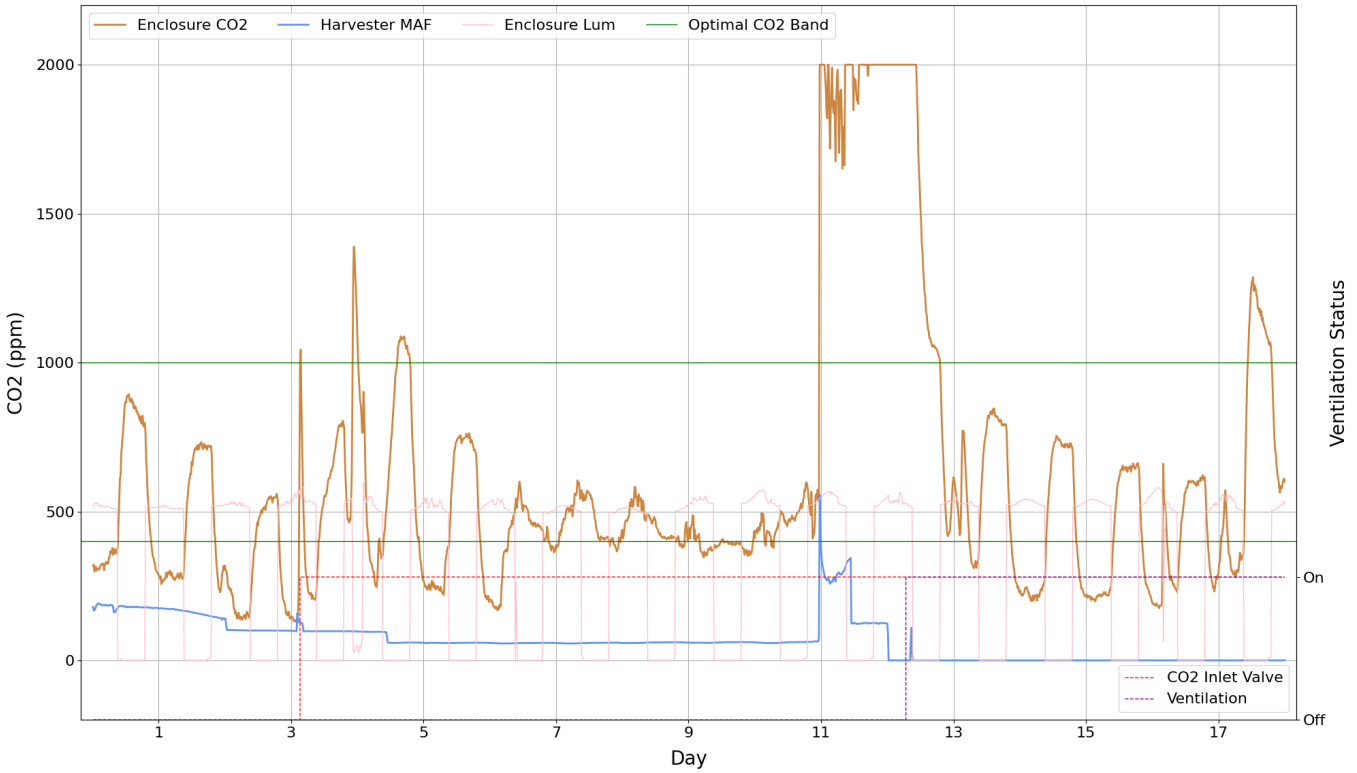

FIGURE 4.15: CO_2 harvester flow graph.

4.14 Temperature Analysis of CO_2 in the Harvesting Process

The temperature dynamics of CO_2 gas as it passed through the harvester were analysed using a temperature sensor placed in the CO_2 sensing unit. This allowed for a direct

comparison between the temperature of the CO_2, the ambient temperature, and the temperature within the enclosure. Initially, it was hypothesised that the CO_2, despite being produced by a mildly exothermic reaction, would cool upon release due to adiabatic expansion.

Contrary to our expectations, the temperature data consistently showed that the CO_2 was warmer than the ambient air. Upon further investigation, this was attributed to the routing of the gas line across the brewery's ceiling, which is situated close to a poorly insulated roof. This placement most likely contributed to the elevated gas temperatures observed which caused by both roof sunload, and overall heat accumulation from the industrial equipment in the facility.

From the collected data, the harvested CO_2 generally maintained a temperature range close to that of the ambient air, with an average temperature difference of 4.1°C for the ambient versus 5.1°C for the harvested CO_2. The collected data is displayed in Figure 4.16 and shows the daily average temperature of the CO_2 was consistently approximately 2 degrees higher than the ambient temperature, aligning with the earlier explanation regarding the influence of the gas line's proximity to the roofing.

Based on these findings, it was concluded that the temperature of the CO_2 in the context of future system designs does not require significant adjustments or meticulous control. Given the required quantity being introduced and the mild temperature differences observed there was no apparent requirement for cooling of heating of the gas.

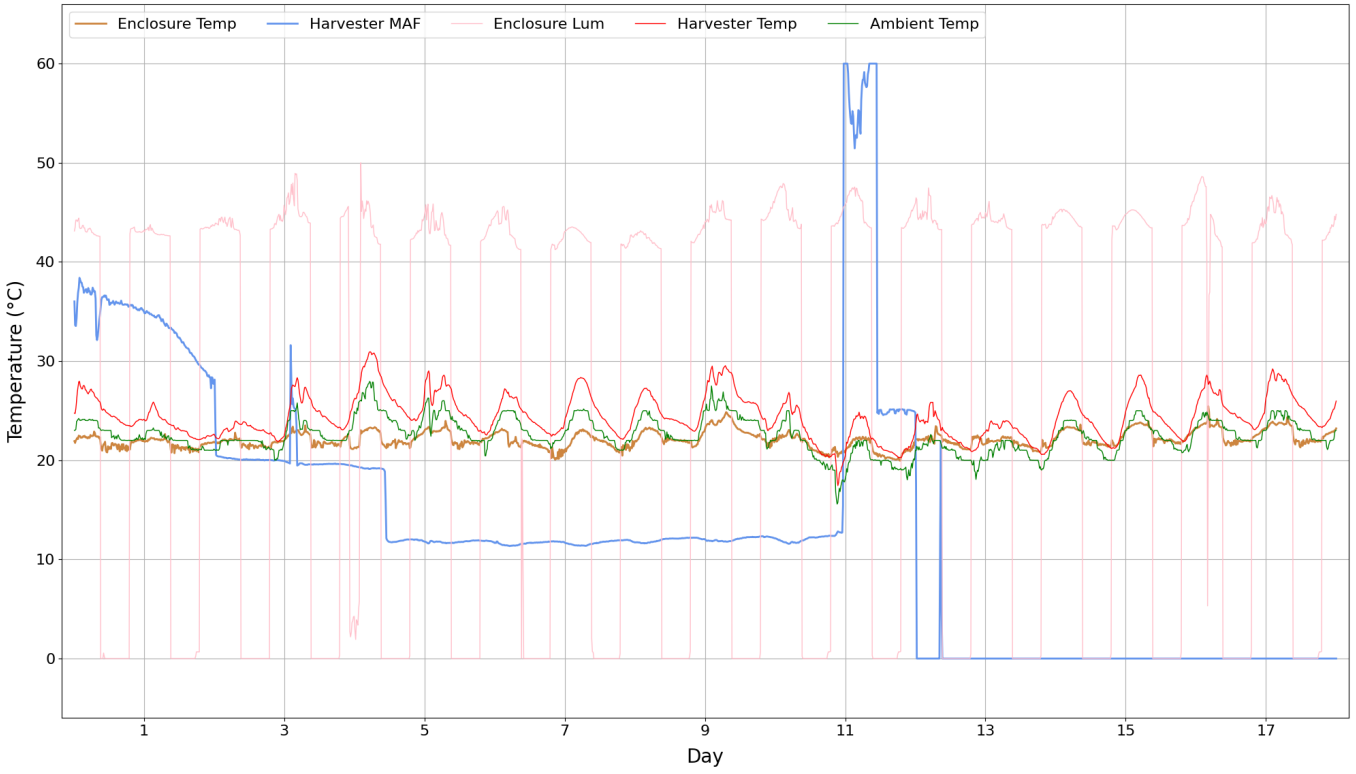

FIGURE 4.16: CO_2 harvester gas temperature graph.

4.15 Humidity Analysis of CO_2 in the Harvesting Process

The humidity levels of the captured CO_2 were analysed, this is a variable of interest due to the energy-intensive nature of humidity removal in a traditional gas bottling processes. With the goal of utilising raw, unfiltered CO_2 for agricultural purposes, the aim was to identify discernible trends in humidity relative to CO_2 flow rates, and understand the overall spread of the humidity in the scavenged gas source.

Over the 17 day trial which is displayed in Figure 4.17, two distinct trends emerged. Firstly, at lower CO_2 flow rates, there was a notable alignment between the internal humidity levels of the harvester and the captured gas, typically exhibiting lower overall humidity. Conversely, increases in CO_2 flow rates were correlated with rises in the humidity levels of the harvested gas, peaking at 84% RH, with an average daily value of 66% RH.

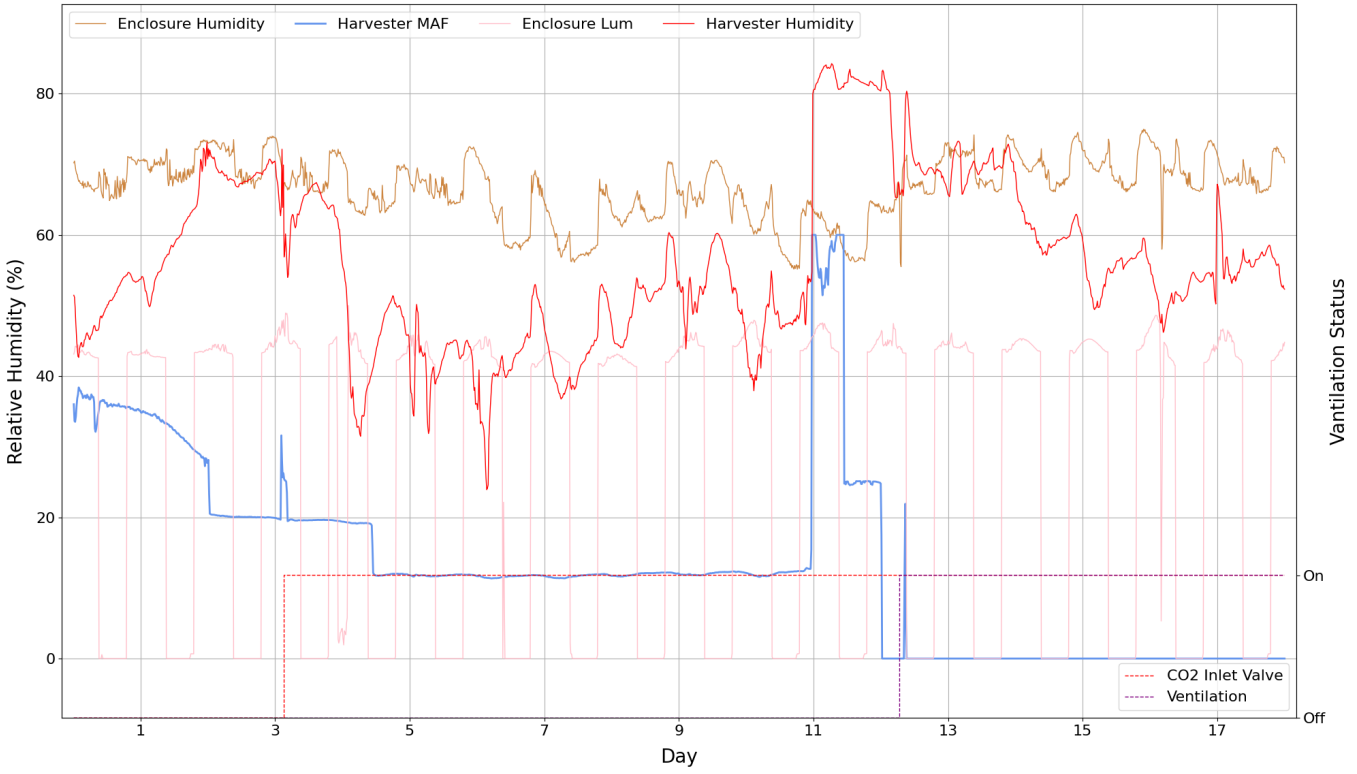

FIGURE 4.17: CO_2 harvester gas humidity graph.

Considering the implications of working with high-humidity gases, concerns such as the potential impact on mechanical systems including valves and compressors must be mitigated. However, given a target ideal value of around 70% RH for hydroponic systems, the average readings align with this target. Variability in the incoming gas stream's humidity can be effectively managed using the hydroponic system's existing humidity controls, which suggests that humidity modulation may be excluded from the system design of similar recovery systems without significant risk.

It is important to note potential sources of error that could influence these findings. The humidity measurements were conducted using a typical capacitive RH sensor, which operates based on polymer absorption. Although this sensor is generally used for direct air streams, it was anticipated that it would perform adequately in a CO_2 gas stream. Ideally, sensors calibrated specifically for CO_2 would provide more accurate data; however, such sensors were not readily available to us. This limitation would most likely only affect

the values directly attributed to the maxima and minima and not the trend but must be considered when interpreting the data.

4.16 Raw CO_2 Gas Composition Discussion

Afte the panel of tests were performed there were only a handful of items which were outside the required specification for food grade CO_2. We will discuss these in the context of its use for agriculture in hydroponics.

The moisture level is significantly higher than the specification target of less than 20 ppm (2100 ppm). However high moisture content as measured in parts per million is unlikely to have any negative effect on its use for hydroponics when weighed against the massive amount of humidity which is generated through transpiration and evaporation of water in the enclosure.

Oxygen Levels were over the specification (36 ppm vs. less than 30 ppm), however this was not considered problematic given the small magnitude and the fact there is oxygen naturally in the enclosure to begin with, but this could have implications for other uses where exposure to oxidisers is more critical.

Similarly the addition of small amounts of nitrogen and argon where not considered problematic as they are already present in air and are low reactivity gasses.

Carbon Monoxide was above the specification (11 ppm vs. less than 10 ppm). This was considered such a small increase that it was negligible.

The level of acetaldehyde is above the specification (7 ppm vs. less than 0.2 ppm), while this compound can be toxic in high levels, Safe Work NSW exposure limits are listed as less than 20 ppm and the concentration of 7 ppm is relatively low.

The most troubling finding was that total Volatile Hydrocarbons were significantly higher than the specification rate, 2520 ppm vs. less than 20 ppm. High levels of hydrocarbons could be harmful to both plant health and human workers. This attribute was particularly interesting given that we did not see any methane present with a test result of less than 0.5 ppm.

The result for ethanol content was recorded as 1220 ppm and this likely contributes significantly to the TVHC reading determined above. Given this high reading and ethanol's affinity for water solubility future iterations of the harvester system would likely benefit from a simple water bubble column filter which could be added for very little cost.

It would be particularly interesting to perform this type of testing with a larger budget to allow simultaneous comparison between the gasses captured raw and different low cost filtration mechanisms.

Overall the TVHC content was a concerning finding however no deleterious effects were observed on plant health during our CO_2 experiments. However it was found that entering the chamber gave a scent of what is best described as "beer" odour. This odour was typically present all throughout the brewery, however when enriching the growth chamber it was amplified.

Its extremely difficult to completely understand the effects of TVHC content given that we cannot identify the entire distribution in the sample. The tests for specific volatile oxygenates came back mostly negative with the exception of ethanol, and aromatic hydrocarbon tests were also negative. An estimation calculation was performed to determine proportional rise in the enclosures TVHC when using the raw gas, the estimation methodology is described in Appendix D.

In the estimation, the scenario was considered to raise the CO_2 level to that more conducive for plant growth (400 ppm to 1500 ppm) using the raw CO_2. It resulted in an estimated corresponding rise of 2.7 ppm of contaminants in the chamber. This is of course an example simplified calculation not taking into account the dynamic factors:

1. Variable gas supply rate
2. Variable contaminant rate
3. Ventilation rate for enclosure
4. Distribution of hydrocarbon compounds
5. CO_2 consumption rate of plants

With regards to exposure by workers, Safe Work NSW lists ethyl alcohol air quality standards for an 8 hour work day to be below 1000 ppm [106]. In this hypothetical the exposure is well below this threshold. However, this is not conclusive as the fractions of volatile compounds are unknown. Given these results it would certainly be prudent to:

- Monitor VOC levels in existing breweries as a safety precaution.
- Ensure that any system based of these designs incorporates gas alarms for CO_2 and VOC.

Overall the CO_2 extracted directly from the fermenters showed a surprisingly high purity rate of 99.975 which exceeded the overall ISBT 2.0 level of 99.9. The distribution of contaminants was varied with some being inconsequential and others certainly worth monitoring. There is a clear need for more gas testing across different stages of fermentation and using different recipes to extract trends in the composition of impurities specifically for hydroponics which is not concerned with oxygen levels and moisture content in contrast to most industrial uses. The results found through this trial system do not indicate any direct reason why raw fermentation CO_2 cannot be used directly in hydroponics without the requirement for expensive and energy intensive purification systems. With further technological development there exists a plethora of potential system designs which could form a strong a symbiosis and directly utilise the CO_2.

Chapter 5

Conclusions and Future Work

5.1 Summary

This thesis explores, for the first time, how a live brewery can host a commercial-scale vertical hydroponic farm that captures and re-uses its own fermentation off-gas. A 440-pod wall enclosure (379 plants in the reported testing) was installed on the brewhouse floor and linked to an IoT control stack built with Node-RED, MQTT and InfluxDB time-series backend. The stack regulated light, temperature, humidity, pH and EC, and periodically injected raw CO_2 drawn straight from the fermenters. Continuous logging showed that the sealed enclosure would reach daytime lows of 130 ppm without supplementation. Transient peaks ¿ 1000 ppm when dosing were experienced (due to oversupply), confirming that brewery waste gas can meaningfully supplement and control the environmental CO_2 without bottled cylinders or any additional purification. Samples of the harvested gas were tested using chromatography techniques and minimal contamination was reported its raw state and no negative effects on plant health were observed.

Core set-points for climate and nutrient dosing were held within their target bands throughout the reported lettuce production cycle, and long term deviations and profile drift were considered and reported on based on over 12 months of testing and validation. The automation layer and the practical compatibility of brewing and controlled-environment agriculture was considered. Non linear production of CO_2 from the brewery's fermenters

was shown to exceed the control capabilities of the prototype harvester system, and proved more difficult than expected to optimise without buffering. The medium scale prototype builds on existing IoT-hydroponic research from bench-scale experiments to an industrial context while laying the groundwork for future work on full scale CO_2 control automation, yield optimisation and further brewery-farm symbiotic refinement.

5.2 Research Question 1

Can a commercial-scale hydroponic system be created within a working brewery using an IoT-based automation system to both control environmental variables and dynamically introduce brewery CO_2 for enrichment?

This research question stems from the processing advantages from being in the direct vicinity of the brewery CO_2 source. By being inside, or directly adjacent to the fermentation area it is possible to direct CO_2 from these operations to the hydroponic farm. The research presented confirms that a commercial-scale hydroponic system can indeed be successfully integrated within an operational brewery environment. By utilising IoT-enabled automation, the system developed was able to control key environmental factors such as temperature, humidity, light, and CO_2 concentration, enabling the controlled environment to emulate the ideal growth conditions extracted from literature. The IOT system employed commercially available sensors and open-source software, reducing the cost and enabling real-time data collection and automation of tasks like irrigation and nutrient dosing.

The most novel aspect of this integration was the utilisation of raw brewery CO_2, which provides an environmentally sustainable approach to CO_2 enrichment for the hydroponic system. The research showed that brewery CO_2, a byproduct of fermentation, could be effectively harnessed to enrich the internal atmosphere without requiring the expensive, energy-intensive processing typically associated with commercial CO_2 capture systems which bottle the gas. The described prototype harvester was able to be retrofitted onto the existing brewery equipment and be produced for an extremely low cost.

However, challenges did arise during the deployment of the system, particularly in ensuring consistent CO_2 delivery during the large fluctuations in brewery operations. Future work would incorporate a buffering mechanism to stabilise the supply side of the equation. Despite this, the research illustrates that direct CO_2 enrichment appears viable and could be scaled to commercial levels with appropriate technological development. Ultimately offering both industries a sustainable, mutually beneficial arrangement.

5.3 Research Question 2

What insights can be gained from fully integrating the IOT control system with advanced data capture methods, and performing experiments at a larger scale.

The integration of IOT technology into the hydroponic system allowed for significant environmental insights that directly impact the efficiency of the system. The system was equipped with sensors that continuously monitored critical parameters such as temperature, humidity, light levels, and nutrient concentrations. This data was then processed in real-time by the Node-Red based automation software, allowing the system to make dynamic adjustments to environmental controls.

From analysis of data over a longer period of time and the use of multiple sensors a number of novel findings were presented:

- Hydroponics systems in current literature typically monitor nutrient temperature at the tank location. This research revealed that upon scaling such a setup there is a large deviation in the tank temperature and that actually experienced at the root zone due to piping heat losses.
- Dosing systems described using smaller tanks are able to iterate faster due to the short time required for mixing and ultimate stabilisation after dosing. Operation of this system revealed that as the tank size scales the amount of time required to reach equilibrium is increased and this has the effect of reducing the number of times dosing can accurately be initiated per day.

- The research demonstrated that the typical hydroponics grow lights commercially available for sale are far from optimised in terms of light distribution and spread, despite fine grained electronic control complete optimisation of PAR was not possible for all plants. There is significant scope for research into matrix based addressable lighting which targets a specific plant allowing for feedback from PAR testing to be automated.

- The deviation between measurements of the same variable across the enclosure reveal that the dynamic environment inside the enclosure lends itself far more to arrays of sensors than individual ones. Single sensors were shown to not be able to be relied upon given the variation in results based on placement location.

- HVAC considerations at this medium scale were shown to be more important than in smaller experiments. Despite the significant size of the implemented air conditioning system relative to the enclosure it was not possible under all circumstances to maintain optimum temperature. This was caused primarily due to the large variance introduced by the lighting switching off at the conclusion of the photo-period.

- The potential for passive heating/cooling appears possible when the analysis of daytime and nighttime temperature deltas and nutrient temperature is considered. This is another potential area for future research to allow the nutrient reservoir to act as a thermal battery and help stabilise the internal temperature.

- Longer term operation revealed the potential for mould and algae contamination which appeared after continued use of the system.

- CO_2 monitoring during periods of full environmental isolation revealed an oscillating downward CO_2 trajectory and raises interesting opportunities for research in collaboration with biologists.

- The specific combination of vertical hydroponics and lettuce cultivation was tested on multiple hydroponic substrates and the controlled nature of the environment allowed for the novel extraction of the most performant substrate, which was revealed to be Grow Wool in this configuration.

5.4 Research Question 3

To what extent can raw, unprocessed CO_2 from breweries be practically and efficiently utilised in hydroponic systems without requiring energy-intensive processing?

The research conducted on utilising raw, unprocessed CO_2 from brewery fermentation showed promising results for its practical application in hydroponic systems. This novel concept presented several concerns from an implementation perspective which were addressed in the study. Firstly it was unclear how transportation and control of the gas under extremely low pressure could be accomplished given no prior systems exist. The described prototype CO_2 harvesting system was able to divert fermentation CO_2 directly into the hydroponic chamber, allowing for electronic control of the gas to be either vented to atmosphere or ingested by the system. Further, it was able to be retrofitted onto existing fermentation systems and the minimal back pressure appeared to have no effect on the breweries operation. Secondly, concerns existed regarding potential contaminants being present in the gas. This was addressed by the design of the novel sampling system which was able to produce high pressure raw CO_2 canisters allowing for gas chromatography to be performed. The high cost of this analysis technique prohibited comprehensive testing across different stages of fermentation, however the preliminary results did not reveal any large concentrations of toxic gasses and a purity rate of 99.975% was returned. Further, no deleterious effects were observed during the experiments conducted.

The research results showed that raw brewery CO_2 could be efficiently transported and used for enrichment in hydroponics, and revealed no major barrier to the implementation of this technology. Further testing would need to be performed on various beers, and throughout various stages of the fermentation process to reach a firm conclusion on the variability of the gas purity. Further experiments with raw fermentation CO_2 compared directly to purified bottled CO_2 would also provide further insights, however this would require the development of a high pressure large bottling system for the raw gas and collaboration with biology domain experts to form firm conclusions.

Given the large energy and complexity savings involved in this concept coupled with the transportation and urban location of micro-breweries the concept warrants further research

and development.

5.5 Future Work

Conventional bottled CO_2 carries an energy and freight penalty. Co-locating hydroponic farms with breweries allows them to tap the gas already produced on site, cutting transport, refrigeration and cylinder costs while valorising a waste stream. The prototype presented here, installed inside a Sydney brewery, demonstrates that concept at a medium scale. A sealed vertical enclosure was linked to a Node-RED/MQTT/InfluxDB control stack that diverted raw fermenter gas into the enclosure when the commanded set-point threshold was exceeded. The experiments performed confirm basic technical viability without disrupting brewing operations.

Key lessons learned from year-long trial

- **Automation states**: Power cycles and maintenance tasks occasionally drove the system outside safe ranges. Defining explicit modes of operation or a state matrix (startup, cleaning, reboot) and associated logic would improve resilience and reduce operator error.
- **Hardware Selection**: Dripper calcification emerged as a recurring maintenance task. Future designs should optimise dripper nozzle shape to combat this. Lighting choice showed plant-level LED matrices would potentially even out PAR distribution and eliminate observed hot-spots.
- **Thermal management**: Switching between heating and cooling on the same day exposed the limits of off-the-shelf HVAC algorithms. Coupling nutrient reservoirs to passive heat sinks and designing for higher thermal mass warrants further investigation.
- **CO_2**: CO_2 production is highly non linear a suitable buffering mechanism is required to even out production vs consumption for the for the harvester design to allow smoother injection control.

Next engineering steps

Before the prototype can mature into a production-ready installation, several technical refinements must be tackled:

1. *Buffer storage*: Install low-pressure bladder or small-scale compression to smooth gas supply during cleaning and batch changeovers.
2. *Contaminant profiling*: Extend purity assays across beer styles and fermentation stages to confirm suitability for sensitive crops.
3. *Harvester iteration*: Alternative designs and control systems to optimise the delivery of the produced CO_2.

Two clear avenues for further development can be realised using the novel concept:

1. **Direct use**: Build farms adjacent to breweries and pipe raw gas straight into sealed grow rooms, this is clearly the highest resource-efficiency option where real estate permits.
2. **Minimal-process bottling**: Compress and distribute an "ag-grade" CO_2 that meets horticultural but not beverage standards for human consumption, broadening the market to urban farms and allowing local delivery without cryo-freezing.

Whichever route proves most practical, the shared upside for brewers and growers is consistent:

- Shrink capital expenditure on cylinder production and cryo-refrigeration.
- Reduce transport emissions; when co-located, they fall to zero.
- Simplify brewery infrastructure by removing high-pressure purification requirements and associated energy burden.
- Lower greenhouse HVAC loads by maintaining elevated CO_2 with minimal external ventilation.

Rising urban brewery numbers and the horticulture sectors demand for sustainable intensification make brewery-farm symbiosis an attractive option. This study supplies the first medium-scale evidence that such integration is technically feasible with inexpensive sensors and open-source controls, while also mapping the chief hurdles that remain. Addressing buffer storage, contaminant assurance and hardware durability will be required steps toward turning vent-gas into a dependable agricultural input and, ultimately, embedding food production within or adjacent to brewing operations. It is hoped that future projects can enable this relationship and reap the advantages associated.

Appendix A

Substrate Experiment Dataset

Table A.1: Growth media data table

Cocoballs				Vermiculite				Grow Wool				Mix			
W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col
13	180	UD	1	0		EP	1	40	170	UD	1	29	200	UD	1
32	180	H	1	69	140	DH	1	6	40	UD	1	141	240	H	1
0	0	EP	1	52	160	H	1	98	170	H	1	215	116	H	1
49	200	H	1	77	165	H	1	158	220	H	1	104	200	H	1
66	200	H	1	106	195	SB	1	83	190	H	1	86	215	H	1
60	200	H	1	46	160	UD	1	120	190	H	1	60	175	H	1
22	150	UD	1	53	165	UD	1	158	215	H	1	0	0	EP	1
31	140	H	1	36	140	UD	1	82	210	H	1	53	180	H	1
51	180	H	1	51	165	UD	1	124	230	H	1	70	190	H	1
69	230	H	1	0	0	EP	1	128	180	H	1	0	0	EP	1
100	220	H	2	77	170	H	2	32	190	UD	2	83	230	H	2
13	200	UD	2	106	190	H	2	135	220	H	2	90	195	H	2
33	150	UD	2	77	190	SB	2	71	220	H	2	78	200	H	2
9	170	UD	2	63	145	SB	2	155	190	H	2	87	190	H	2
27	180	UD	2	103	170	SB	2	115	180	HD	2	160	230	H	2
50	220	H	2	89	165	SB	2	81	180	H	2	86	200	H	2
68	200	H	2	87	170	SB	2	80	190	H	2	67	180	UD	2
88	220	H	2	98	190	H	2	65	180	H	2	80	190	SB	2
19	180	UD	2	68	180	H	2	106	200	H	2	64	190	SB	2
6	140	UD	2	33	130	UD	2	42	200	H	2	45	190	H	2
31	160	UD	3	43	160	H	3	145	230	H	3	0	0	EP	3
50	180	H	3	45	175	H	3	48	150	H	3	88	210	H	3
40	170	H	3	76	190	H	3	167	180	H	3	141	210	SB	3
47	200	H	3	94	175	H	3	124	190	H	3	165	220	SB	3
9	210	UD	3	66	160	H	3	170	185	H	3	98	175	SB	3
52	190	H	3	95	180	H	3	140	200	H	3	0	0	EP	3

Legend: UD: Under developed, EP: Empty pot, DH: Double healthy, H: Healthy, B: Some browning, SB: Some burning, VB: Very burned

Cocoballs				Vermiculite				Grow Wool				Mix			
W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col
12	170	UD	3	101	190	H	3	115	200	H	3	52	200	SB	3
40	200	H	3	0	0	EP	3	82	160	H	3	37	160	UD	3
47	200	H	3	0	0	EP	3	88	190	H	3	47	175	UD	3
26	190	UD	3	57	155	H	3	66	200	H	3	0	0	EP	3
89	230	SB	4	145	15	UD	4	110	220	H	4	64	210	H	4
73	160	H	4	63	155	H	4	39	130	UD	4	115	215	H	4
77	150	H	4	104	180	H	4	115	170	H	4	110	210	H	4
48	230	H	4	96	180	H	4	123	170	H	4	175	230	H	4
5	160	UD	4	82	180	H	4	65	180	H	4	107	175	VB	4
81	170	H	4	95	185	H	4	113	170	H	4	78	175	H	4
84	190	H	4	0	0	EP	4	32	150	H	4	110	190	H	4
57	200	H	4	0	0	EP	4	0	0	EP	4	75	175	H	4
41	185	H	4	0	0	EP	4	65	180	H	4	0	0	EP	4
58	140	H	4	56	170	H	4	65	190	H	4	67	210	H	4
56	180	H	5	38	175	H	5	0	0	EP	5	76	200	H	5
82	210	H	5	70	190	H	5	47	160	UD	5	70	185	H	5
71	180	H	5	145	190	H	5	86	170	H	5	75	135	SBD	5
120	210	H	5	132	170	HD	5	135	180	H	5	0	0	EP	5
51	180	H	5	180	190	SB	5	296	240	HD	5	115	170	SB	5
57	170	H	5	87	150	SB	5	118	175	H	5	0	0	EP	5
41	150	H	5	0	0	EP	5	113	220	HD	5	139	210	DSB	5
12	190	H	5	0	0	EP	5	116	185	H	5	78	175	SB	5
61	230	H	5	60	150	SB	5	56	190	H	5	15	140	UD	5
126	200	H	5	28	150	SB	5	50	170	H	5	0	0	EP	5
86	170	H	6	0	0	EP	6	145	210	H	6	77	200	H	6
61	170	H	6	123	220	H	6	180	240	H	6	116	200	H	6
94	200	H	6	139	210	H	6	185	190	H	6	121	195	SB	6
76	200	H	6	148	230	SB	6	210	235	H	6	0	0	EP	6
66	170	H	6	111	200	H	6	122	170	H	6	0	0	EP	6
69	190	H	6	0	0	EP	6	0	0	EP	6	0	0	EP	6
13	160	H	6	63	150	H	6	0	0	EP	6	91	180	H	6
40	180	H	6	50	160	H	6	0	0	EP	6	63	190	H	6
66	200	H	6	25	155	H	6	0	0	EP	6	0	0	EP	6
117	230	H	6	0	0	EP	6	0	0	EP	6	0	0	EP	6

Legend: UD: Under developed, EP: Empty pot, DH: Double healthy, H: Healthy, B: Some browning, SB: Some burning, VB: Very burned

Cocoballs				Vermiculite				Grow Wool				Mix			
W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col
60	160	H	7	0	0	EP	7	51	160	H	7	55	180	H	7
95	200	H	7	130	250	H	7	127	190	H	7	59	200	H	7
132	220	DH	7	85	190	H	7	150	200	H	7	104	220	H	7
22	160	H	7	173	180	H	7	83	180	H	7	0	0	EP	7
66	200	H	7	120	170	H	7	106	180	H	7	0	0	EP	7
73	210	H	7	72	160	H	7	0	0	EP	7	0	0	EP	7
31	200	H	7	76	165	H	7	0	0	EP	7	0	0	EP	7
103	210	H	7	68	155	H	7	0	0	EP	7	41	190	H	7
170	210	H	7	33	150	H	7	0	0	EP	7	0	0	EP	7
41	200	H	7	32	150	H	7	0	0	EP	7	0	0	EP	7
127	200	H	8	74	170	H	8	105	190	H	8	99	200	H	8
143	200	H	8	56	175	SB	8	110	200	H	8	92	200	H	8
142	230	H	8	140	200	SB	8	187	210	H	8	36	145	UD	8
120	220	H	8	87	165	H	8	160	200	HD	8	154	220	HD	8
68	160	H	8	122	180	H	8	76	150	VB	8	112	200	H	8
54	180	H	8	135	170	H	8	0	0	EP	8	0	0	EP	8
35	160	H	8	32	130	UD	8	99	200	H	8	42	190	H	8
67	220	H	8	62	170	H	8	0	0	EP	8	13	150	UD	8
102	200	H	8	31	155	H	8	0	0	EP	8	27	140	UD	8
141	220	H	8	34	160	H	8	0	0	EP	8	30	140	UD	8
120	190	H	9	19	130	UD	9	69	220	H	9	67	200	H	9
237	240	SB2	9	108	180	H	9	118	220	H	9	33	170	UD	9
158	210	SB	9	22	140	UD	9	105	200	H	9	110	210	H	9
98	160	H	9	125	160	H	9	158	220	H	9	106	215	HD	9
100	160	H	9	170	103	SB	9	196	190	H	9	0	0	EP	9
26	110	UD	9	128	160	SB	9	110	200	H	9	0	0	EP	9
27	120	UD	9	108	160	H	9	162	220	HD	9	50	170	H	9
87	180	H	9	112	180	SB	9	0	0	EP	9	62	170	H	9
131	220	SB	9	39	145	UD	9	0	0	EP	9	25	180	UD	9
127	220	SB	9	34	160	UD	9	0	0	EP	9	16	130	UD	9
113	190	SB	10	46	165	UD	10	145	250		10	30	180	UD	10
114	220	H	10	60	180	H	10	0	0	EP	10	0	0	EP	10
100	180	H	10	93	170	H	10	0	0	EP	10	67	210	H	10
84	170	TS	10	74	170	H	10	120	190	H	10	105	210	H	10
47	160	H	10	75	170	SB	10	132	210	H	10	67	200	H	10
83	160	H	10	104	180	SB	10	110	190	H	10	0	0	EP	10
40	130	UD	10	26	120	UD	10	128	190	H	10	0	0	EP	10
7	100	UD	10	36	150	H	10	0	0	EP	10	48	190	H	10
94	220	H	10	41	160	UD	10	0	0	EP	10	0	0	EP	10
110	220	H	10	15	110	UD	10	0	0	EP	10	0	0	EP	10

Legend: W: Weight of plant (g), L: length of plant (mm), C: comment on overall appearance, Col: location of plant (column), UD: Under developed, EP: Empty pot, DH: Double healthy, H: Healthy, B: Some browning, SB: Some burning, VB: Very burned

Cocoballs				Vermiculite				Grow Wool				Mix			
W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col	W (g)	L (mm)	C	Col
140	210	HD	11	62	200	H	11	81	190	H	11	46	210	H	11
220	225	H	11	69	180	H	11	44	175	H	11	85	200	H	11
48	130	H	11	125	190	H	11	58	165	H	11	30	180	H	11
123	200	H	11	51	150	UD	11	155	200	SB	11	57	175	H	11
110	190	H	11	86	165	SB	11	121	205	H	11	0	0	EP	11
52	160	H	11	36	120	SB	11	152	235		11	0	0	EP	11
81	180	H	11	72	175	H	11	0	0	EP	11	0	0	EP	11
6	150	UD	11	106	190	H	11	0	0	EP	11	0	0	EP	11
13	160	UD	11	48	150	UD	11	81	220	H	11	12	150	UD	11
20	150	UD	11	22	135	UD	11	0	0	EP	11	0	0	EP	11

Legend: W: Weight of plant (g), L: length of plant (mm), C: comment on overall appearance, Col: location of plant (column), UD: Under developed, EP: Empty pot, DH: Double healthy, H: Healthy, B: Some browning, SB: Some burning, VB: Very burned

Appendix B

Statistical Tables

Table B.1: System parameter summary day -5 to day -1.

Variable	**Min**	**Max**	**Avg**	**Range**
Tank Ec	10.2	10.5	10.3	0.2
Tank pH	5.6	5.9	5.8	0.3
Enclosure Humidity1	36.2	50.0	44.1	13.8
Enclosure Humidity2	35.0	50.2	43.6	15.2
Outside Humidity	39.0	40.4	39.8	1.4
Enclosure Temp2	25.3	30.3	27.8	5.0
Outside Airtemp	17.2	20.0	18.3	2.8
Enclosure Temp1	26.4	31.3	28.8	4.9
Enclosure CO_2	360.7	731.5	450.9	370.8
Enclosure Lum	0.0	938.1	533.6	938.1
Tank Temp	21.2	21.5	21.4	0.3
Return Watertemp	18.6	19.8	19.3	1.1

TABLE B.2: System parameter summary day 1 to day 17.

Variable	**Min**	**Max**	**Avg**	**Range**
Tank Ec	11.2	13.4	12.1	2.2
Tank pH	NaN	NaN	NaN	NaN
Enclosure Humidity1	45.6	56.8	51.5	11.2
Enclosure Humidity2	65.2	93.1	80.2	27.9
Outside Humidity	38.0	42.8	40.2	4.8
Enclosure Temp2	15.4	23.3	20.3	7.9
Outside Airtemp	12.2	21.0	17.1	8.8
Enclosure Temp1	24.6	29.9	27.9	5.3
Enclosure CO_2	233.3	929.5	456.0	696.2
Enclosure Lum	0.0	1457.2	768.3	1457.2
Tank Temp	19.1	20.8	20.1	1.7
Return Watertemp	16.5	19.3	18.5	2.9

TABLE B.3: System parameter summary day 18 to day 21.

Variable	**Min**	**Max**	**Avg**	**Range**
Tank Ec	10.9	13.0	11.5	2.1
Tank pH	5.7	7.9	6.4	2.2
Enclosure Humidity1	44.7	53.3	49.0	8.5
Enclosure Humidity2	65.3	85.1	74.9	19.9
Outside Humidity	38.9	41.0	39.9	2.1
Enclosure Temp2	15.8	22.4	19.7	6.6
Outside Airtemp	15.4	20.1	17.7	4.7
Enclosure Temp1	23.6	29.2	26.7	5.7
Enclosure CO_2	225.6	1167.5	542.2	941.9
Enclosure Lum	0.0	1438.8	817.0	1438.8
Tank Temp	18.7	20.9	19.9	2.2
Return Watertemp	16.6	19.3	18.3	2.7

TABLE B.4: System parameter summary day 21 to day 25.

Variable	**Min**	**Max**	**Avg**	**Range**
Tank Ec	10.1	12.3	11.3	2.2
Tank pH	3.6	6.7	6.4	3.1
Enclosure Humidity1	48.4	58.4	53.6	10.0
Enclosure Humidity2	71.9	93.2	83.2	21.3
Outside Humidity	38.2	42.0	39.8	3.8
Enclosure Temp2	16.4	22.5	20.4	6.1
Outside Airtemp	13.0	20.8	17.9	7.8
Enclosure Temp1	25.3	29.3	27.8	4.0
Enclosure CO_2	133.4	838.2	401.3	704.8
Enclosure Lum	0.0	1477.2	823.7	1477.2
Tank Temp	19.0	20.6	20.0	1.6
Return Watertemp	17.0	19.0	18.5	2.0

TABLE B.5: System parameter summary day 26 to day 30.

Variable	**Min**	**Max**	**Avg**	**Range**
Tank Ec	9.7	11.5	10.4	1.8
Tank pH	6.4	7.2	6.7	0.8
Enclosure Humidity1	44.9	60.7	52.3	15.8
Enclosure Humidity2	65.7	88.4	78.1	22.7
Outside Humidity	37.0	40.1	38.8	3.1
Enclosure Temp2	16.4	23.0	20.4	6.6
Outside Airtemp	17.0	23.1	20.0	6.1
Enclosure Temp1	22.2	29.4	26.9	7.2
Enclosure CO_2	338.9	1089.6	639.2	750.6
Enclosure Lum	0.0	1466.0	757.2	1466.0
Tank Temp	18.6	21.5	20.4	2.8
Return Watertemp	17.1	20.2	19.1	3.1

Appendix C

Gas Chromatography Results

Sample Number: ACS2335479-1

Analysis performed by ACS Laboratories

Analyte	**Method**	**Units**	**Specification**	**Results**
Assay	ISBT 2.0	% (v/v) 0.005	>99.9	>99.975
Moisture	ISBT 3.0	ppm (v/v) 20	<20	2100
Ammonia	ISBT 6.0	ppm (v/v) 0.5	<2.5	<0.5
Oxygen	ISBT 4.0	ppm (v/v) 4	<30	36
Nitrogen	ISBT 4.0	ppm (v/v) 4	na	165
Argon	ISBT 4.0	ppm (v/v) 4	na	6
Nitric oxide	ISBT 7.0	ppm (v/v) 0.5	<2.5	<0.5
Nitrogen Dioxide	ISBT 7.1	ppm (v/v) 0.5	<2.5	<0.5
Non volatile Residue (particulates)	ISBT 8.0	ppm (mg/Kg) 10	<10	NA
Non volatile Residue (Oil and Grease)	ISBT 8.0	ppm (mg/Kg) 5	<5	NA
Phosphine	ISBT SM 3.0	ppm (v/v) 0.1	<0.3	NR
Total volatile Hydrocarbons (as methane)	ISBT 10.0	ppm (v/v) 0.5	<20	2520
Methane	ISBT 4.0	ppm (v/v) 0.5	<50	<0.5
Acetaldehyde	ISBT 11.0	ppm (v/v) 0.05	<0.2	7
Benzene and other aromatic Hydrocarbons	ISBT 12.0	ppb (v/v) 2	<20	<2
Carbon monoxide	ISBT 5.0	ppm (v/v) 1	<10	11
Methanol	ISBT 9.0	ppm (v/v) 1	<10	0.5
Total Sulphur	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.01
Sulfur Dioxide	ISBT 14.0	ppm (v/v) 0.1	<1	<0.1
Hydrogen	ISBT 4.0	ppm (v/v) 10	na	<10
Helium	ISBT 4.0	ppm (v/v) 10	na	<10
Sulfur Compounds				
Hydrogen sulfide (H2S)	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1

Carbonyl Sulfide (COS)	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Methyl Mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Ethyl Mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Dimethyl Sulfide	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Carbon Disulfide	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
t-Butyl Mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Isopropyl Mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
n-Propyl mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Methyl ethyl sulfide	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
2-Butyl mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Isobutyl mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Diethyl Sulfide	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
n-Butyl mercaptan	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Dimethyl disulfide	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Total Sulphur	ISBT 13.0	ppm (v/v) 0.01	<0.1	<0.1
Speciated Aromatic Hydrocarbons				
Benzene	ISBT 12.0	ppb (v/v) 2	<20	<2
Toluene	ISBT 12.0	ppb (v/v) 2	<20	<2
Ethyl Benzene	ISBT 12.0	ppb (v/v) 2	<20	<2
Xylenes	ISBT 12.0	ppb (v/v) 2	<20	<2
Other aromatics as Toluene	ISBT 12.0	ppb (v/v) 2	<20	<2
Speciated Volatile Oxygenates				
2-Butanol	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Acetone	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Diethyl Ether	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Dimethyl Ether	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Ethanol	ISBT 10.1	ppm (v/v) 0.1	na	1220
Ethyl Acetate	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Hexanes	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Isoamyl Acetate	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Isobutanol	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Isopropanol	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Methyl Ethyl Ketone	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
n-Butanol	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Isoamyl Acetate	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Isoamyl Alcohol	ISBT 10.1	ppm (v/v) 0.1	na	<0.1
Unknown VOX	ISBT 10.1	ppm (v/v) 0.1	na	<0.1

Appendix D

Contaminant Estimation

First the ppm v/v of the contaminant was converter to ml per L of gas assuming standard conditions.

$$\text{Volume of hydrocarbon} = 1000\,\text{mL} \times \frac{2520}{1,000,000} = 2.52\,\text{mL}$$

Then the contamination ride was estimated using a CO_2 purity value of 99% and the dimensions of the enclosure (8m X 3m X 1m) with a required increase of CO_2 level from 400ppm to 1500ppm.

$$V = \text{length} \times \text{width} \times \text{height} = 1\,m \times 6\,m \times 3\,m = 18\,m^3$$

$$\Delta\text{CO}_2 = 1500\,ppm - 400\,ppm = 1100\,ppm$$

$$\Delta V_{\text{CO}_2} = V \times (\Delta\text{CO}_2 \times 10^{-6}) = 18\,m^3 \times (1100 \times 10^{-6}) = 0.0198\,m^3$$

$$V_{\text{total}} = \frac{\Delta V_{\text{CO}_2}}{0.99} = \frac{0.0198\,m^3}{0.99} \approx 0.02\,m^3$$

$$\text{Total Hydrocarbon Volume} = \frac{2.52\,\text{mL/L} \times 20\,\text{L}}{1,000,000\,\text{mL/m}^3} = 0.00005\,\text{m}^3$$

$$\text{PPM of Hydrocarbon In Chamber} = \left(\frac{0.00005}{18}\right) \times 10^6 \approx 2.777\,\text{ppm}$$

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