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# Digital Plant Factories
# Crop Production in Controlled Environments

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Master in Information Systems Management

Supervisor:
Phd Octavian Adrian Postolache, Full Professor,
Iscte-Instituto Universitário de Lisboa

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TECHNOLOGY
AND ARCHITECTURE

Department of Information Science and Technology

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## Resumo

Alterações climáticas, esgotamento dos recursos naturais, poluição, crescimento poplulacional, desigualdades económicas, e alterações de padrões de consumo, são entre outras razões de incerteza para o futuro da produção comida, sua sustentabilidade e desempenho [1], incompatível num cenário de necessidade de aumento necessidades devido ao constante crescimento da população, devendo esta atingir 8,4 mil milhões até 2030 [2], sendo, estes os ingredientes para um colapso civilizacional [1]. Segundo a FAO, "business as usual" não é uma opção, é critico a alteração de paradigmas produtivos, transição para estratégias agrícolas inovadoras que garantam sustentabilidade, atendendo à crescente necessidade de alimentos. Agricultura de ambiente controlado (CEA) parece uma solução coerente.

Esta pesquisa explora uma subclasse de CEA, Fábricas de Plantas (FP), cujo processo de produção em tudo é semelhante à produção industrial, no entanto produz produtos agrícolas em ambiente fechado, com controle total dos fatores produtivos, tais como $CO_2$, luz, temperatura, água e nutrientes, ajustados a condições ótimas para determinado(s) objetivo(s) (ex. rendimento, valor nutricional, consumo de energia, etc). A analogia usada com a produção industrial é intencional, já que este setor já foi sujeito à disrupção digital, definida em conceitos de transformação digital como a *Industrie 4.0*, cujos elementos que permitem a sua realização, tais como Internet das Coisas, Automação, Big Data , Aprendizagem Automática e Inteligência, sendo os mesmos necessários na implementação de FP. Esta tese propõe e prototipa uma arquitetura de referência IoT para PFs, visando a padronização, controlo eficaz e integração potencial de diferentes tipos de cultivares.


***Palavras-Chave:*** Agricultura de precisão, IoT, sustentabilidade, Fábricas de plantas, Industrie 4.0, Arquitetura de Referência.

## Abstract

Climate change, state of natural resources, pollution, population growth, income distribution, consumer awareness, and dietary choices are sources of uncertainty for the future of food and agriculture, its sustainability and performance [1]. An unremittingly growing population expected to reach 8.4 billion by 2030 [2], and this conflicting setting are ingredients for a civilizational collapse [1]. As stated by FAO, "business as usual" is not an option, a paradigm shift is critical, shifting to innovative agricultural strategies, ensuring sustainability while meeting growing food demands. Controlled-environment agriculture (CEA) seems a logical solution.

This research explores one subclass of Controlled Environment Agriculture (CEA), i.e., Plant Factories (PF), that in terms of production process could be analogous to industrial manufacturing. However, instead of producing industrial goods, the output consists of agricultural products, including both crops and fungi, cultivated in a closed system. This system allows for full control of all input variables such as carbon dioxide, light, temperature, water, and nutrients, which are tuned to optimal conditions to achieve specific objectives (e.g., yield, nutritional value, energy consumption, etc.). The analogy used with industrial manufacturing is intentional, as sector has been already subject to digital disruption, captured in digital transformation concepts such as *Industrie 4.0*, whose underlying supporting enablers such as Internet of Things, Automation, Big Data, Machine Learning & Artificial Intelligence (ML/AI) are the same required in the PF. This thesis proposes and prototypes an IoT reference architecture for PFs, aiming for standardization, effective control, and potential integration of diverse cultivar's types.


***Keywords*:** Precision Agriculture, IoT, sustainability, Plant Factories, Industry 4.0, Reference Architecture.

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# List of Abbreviations

- AI: Artificial Intelligence
- CEA: Controlled-Environment Agriculture
- $CO_2$: Carbon Dioxide
- CPS: Cyber-Physical Systems
- EC: Electrical Conductivity
- ERP: Enterprise Resource Planning
- HMI: Human Machine Interface
- HPS: High-Pressure Sodium lights
- IIoT: Industrial Internet of Things
- IIRA: Industrial Internet Reference Architecture
- IoT: Internet of Things
- IT: Information Technology
- LED: Light-Emitting Diode
- MES: Manufacturing Execution System
- MH: Metal Halide lamps
- ML: Machine Learning
- MLC: Machine Learning Control
- MPM: Mechanistic and Physiological Model
- MQTT: Message Queuing Telemetry Transport
- NFT: Nutrient Film Technique
- OEE: Overall Equipment Effectiveness
- OPC UA: Open Platform Communications – Unified Architecture
- OT: Operational Technology
- PAR: Photosynthetically Active Radiation
- PF: Plant Factory
- PFAL: Plant Factory with Artificial Lighting
- PFIoT: Plant Factory Internet of Things
- pH: Potential Hydrogen
- PLM: Product Lifecycle Management
- PPFD: Photosynthetic Photon Flux Density
- PV: Process Variable
- RAMI 4.0: Reference Architectural Model Industrie 4.0
- RH: Relative Humidity
- SCM: Supply Chain Management
- SP: Setpoint
- VF: Vertical Farming
- VPD: Vapor Pressure Deficit
- WSN: Wireless Sensor Network

# Chapter 1 Introduction

## 1.1 Background and Context

The future of global food production faces unprecedented uncertainty. Factors such as climate change, the depletion of natural resources like arable land, fresh water, and phosphorus[3], pollution, relentless population growth, economic inequalities, and shifting dietary patterns collectively challenge the sustainability and performance of current agricultural systems[1]. With the global population projected to reach 8.4 billion by 2030 [2], maintaining food security requires a fundamental shift away from conventional practices.

In response to these pressures, Controlled Environment Agriculture (CEA) has emerged as a promising paradigm. This research focuses on a specific subclass of CEA known as the Plant Factory (PF), particularly those using artificial lighting (PFAL). PFs represent a method of producing crops indoors, independent of external climate conditions and geographical limitations [4][5]. These facilities typically involve cultivating plants in vertically stacked layers, often using soilless techniques like hydroponics or aeroponics, within thermally insulated, near-airtight structures [5]. This approach allows for thorough control over environmental variables such as temperature, humidity, carbon dioxide ($CO_2$) concentration, light spectrum and intensity, water, and nutrient delivery [4]. The term Vertical Farming (VF), first coined by Gibert Ellis Bailey in 1915 [6], is often used interchangeably with PF, although VF specifically refers to the vertical cultivation architecture. Supporting literature might use different names like indoor-farming, botanical internet of things [8], this work adopts the term PF, considering PFAL as synonymous when artificial light is the primary source.

## 1.2 Problem Statement

Despite their potential, Plant Factories face significant hurdles that impede widespread adoption and long-term success. A primary challenge lies in the substantial costs associated with establishing and operating these facilities. Initial installation costs can be significantly higher than traditional greenhouses, estimated by Kozai [5] at around $4 000 USD/m² in earlier assessments, although potentially offset by higher productivity per unit area. Operational costs, particularly energy consumption for lighting and climate control, remain a major concern, with electricity accounting for a substantial portion (18-21%) of total production costs [7][5]. The irony, as highlighted by Kozai et al. [5], is that a large fraction of this energy is used to replace free solar light.

Furthermore, the economic viability and sustainability of PFs are under scrutiny, through the recent wave of bankruptcies among prominent PF companies (e.g., Glowfarms, Fifth Season, Future Crops, Kalera, AeroFarms, AppHarvest, Bowery Farming) between 2022 and 2024 underscores these financial challenges, often attributed to high operating costs (especially energy), overreliance on venture capital, limited crop diversity, and intense market competition [8], [9], [10], [11], [12], [13], [14].

Beyond economics, technological challenges persist. Optimizing the complex interplay of environmental factors to maximize yield, quality, and resource efficiency requires sophisticated monitoring and control systems. However, the PF industry currently lacks standardization in its technological platforms and Internet of Things (IoT) implementations. This heterogeneity leads to difficulties in system integration, limits interoperability between components from different vendors, increases investment risks, and hinders the development of scalable, cost-effective solutions [15], [16], [17], [18]. There is a clear need for optimized, standardized, and robust digital infrastructures to realize the full potential of PFs.

## 1.3 Questions and research goals

The motivation for this research stems from the conviction that digital technologies, particularly those associated with the Industrial Internet of Things (IIoT) and concepts from *Industrie 4.0*, can provide solutions to the challenges facing Plant Factories. If issues of cost, efficiency, and standardization can be addressed, PFs offer significant benefits: increased yields, consistent year-round production irrespective of climate, reduced water usage, minimized pesticide application, enhanced food quality and nutritional value, and the potential for local production closer to consumption in urban areas [1], [5].

This research is driven by the potential to transfer knowledge and technology from more mature industrial sectors, such as manufacturing, which have already undergone digital transformation under the *Industrie 4.0* paradigm [19], [20], [21]. Enablers such as IoT, automation, Big Data analytics, Machine Learning (ML), and digital twins, which are central to *Industrie 4.0*, are directly applicable and essential for optimizing PF operations [15].

Therefore, this research aims to help make PFs more viable, scalable, and accessible by proposing a standardized, cost-efficient PFIoT (Plant Factory Internet of Things) platform. Such a platform would serve as a foundation for automating environmental control, optimizing resource use, and enabling data-driven decision-making. The ultimate goal is to facilitate the wider adoption of PF technology, thereby generating environmental, economic, health, and social benefits, potentially while supporting more versatile and circular cultivation systems that integrate plant and fungal production to leverage their symbiotic or complementary needs.

## 1.4 Research Questions and Objectives

The central research question guiding this thesis is:

**Main Question:** How can an open, standardised, and cost-efficient IoT reference architecture be designed and prototyped to effectively monitor and control the environment in a digital plant factory, potentially integrating diverse cultivation types like plants and fungi?

To address this question, the following specific objectives were established:

1. To conduct a comprehensive review of the state-of-the-art in Plant Factories, including their challenges, the environmental factors influencing crop growth (plants and fungi), biological responses, control systems, and relevant IIoT technologies and reference architectures.
2. To propose a standardized PFIoT reference architecture based on established IIoT principles and reference models (like RAMI 4.0 and IIRA), tailored to the specific needs of Plant Factories.
3. To design and implement a small-scale, functional prototype that demonstrates the core capabilities of the proposed PFIoT architecture, specifically focusing on the integration and control of separate plant and fungal cultivation chambers with automated gas exchaphotonge.
4. To evaluate the performance of the developed prototype in terms of its ability to monitor environmental conditions, execute control commands, maintain setpoints, and manage the integrated system.

## 1.5 Scope and Limitations

This research focuses primarily on the conceptualization, design, and prototyping of the PFIoT *platform architecture* and its core monitoring and control functionalities. The scope includes:

- A literature review covering PF concepts, biological requirements, control theory, and IIoT architectures.
- The proposal of a three-tier PFIoT reference architecture (Edge, Platform, Enterprise).
- The development of a small-scale hardware and software prototype implementing the Edge and Platform tiers for two interconnected chambers (one plant, one fungus).
- Demonstration of basic environmental monitoring (temperature, humidity, $CO_2$) and control (heating, cooling, ventilation, humidification, gas exchange) managed by the platform.

The study is subject to the following limitations:

- **Scale:** The prototype is small-scale and not representative of a commercial PF.

- **Component Selection:** Specific, low-cost hardware (ESP32, Raspberry PI, various sensors/actuators) and open-source software were chosen for the prototype, which may differ from industrial-grade solutions.
- **Duration:** The experimental evaluation period was limited, preventing long-term stability analysis or full crop cycle assessment.
- **Cultivation Complexity:** Only basic environmental parameters (air temperature, humidity, $CO_2$) were actively controlled in a closed loop. Nutrient delivery was manual, and light control was limited to photoperiod management. Plant and fungal growth were observed qualitatively rather than quantitatively measured in detail.
- **Economic Analysis:** A detailed cost-benefit analysis or lifecycle assessment of the proposed architecture or the prototype was beyond the scope of this thesis.
- **Control Algorithms:** Simple control strategies (rule-based) were implemented; advanced ML/AI control was conceptualized but not fully implemented in the prototype.

## 1.6 Thesis Outline

This thesis is organized into seven chapters:

- **Chapter 1 - Introduction:** Present the research context, problem statement, motivation, research questions, objectives, scope, limitations, and the overall structure of the thesis.
- **Chapter 2 - Literature Review:** Provides a comprehensive review of Plant Factories, environmental control factors, biological responses of plants and fungi, sensing and control technologies, control theory applications, and relevant IIoT concepts and architectures, identifying the research gap.
- **Chapter 3 Plant Factory IoT Reference Architecture:** The details of the proposed three-tier PFIoT architecture, explaining its components, functionalities, and design rationale, including considerations for integrating plant and fungal cultivation.
- **Chapter 4 Plant Factory prototype:** Describes the research approach and details the design, implementation (hardware and software), control strategy, and data collection methods used for the small-scale prototype.
- **Chapter 5 - Results and discussion:** Presents the findings from the prototype evaluation, including platform performance, environmental control accuracy, observed gas exchange dynamics, actuator performance, and the impact of external disturbances on the rule-based control system. This chapter also discusses these findings in detail and provides an overall discussion synthesizing the results.
- **Chapter 6 - Conclusions and Future Work:** Checks the purpose and objectives of the investigation, summarizes the key findings and contributions, provides answers to the research questions, discusses the implications and limitations of the research, offers recommendations for future work, and presents final considerations. Presents the limitations and indicates potential future developments in this field as an extended solution.
- **Bibliography-** Lists all the bibliographic references cited throughout the thesis.

# Chapter 2 Literature review

## 2.1 Plant Factories: Concept, Promises, and Challenges

### 2.1.1 Definition and Characteristics

Plant Factories (PF) represent an advanced form of Controlled Environment Agriculture (CEA), characterized by production within enclosed, thermally insulated, and near-airtight structures, typically utilizing artificial lighting as the primary or sole light source (PFAL) [4], [5]. According to Kozai [3], PFALs must meet stringent conditions (Figure 1):

- Opaque structures using only artificial light;
- Near airtightness;
- Soil-free cultivation (e.g., hydroponics);
- Sterile environments with continuous monitoring to minimize pathogens and pests.

Vertical Farming (VF), the practice of growing crops in vertically stacked layers or inclined surfaces [6], is a common architectural feature within PFs designed to maximize space utilization [5]. While often used interchangeably, PF refers to the overall controlled system, whereas VF denotes the spatial arrangement. This thesis uses PF as the primary term.

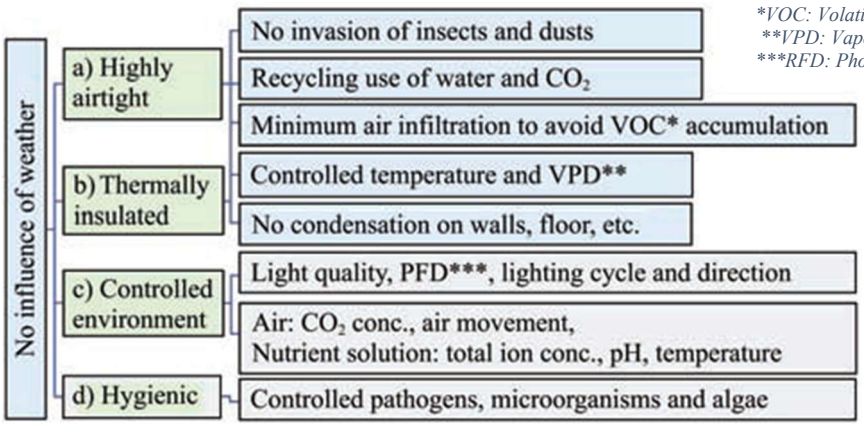



*Figure 1 Main environmental characteristics of the existing PFAL (source* [4]*)*

### 2.1.2 Potential Benefits

PFs offer numerous potential advantages over traditional agriculture. By precisely controlling environmental inputs, they promise higher yields per unit area, faster crop cycles, and year-round production independent of climate or season [5]. Resource efficiency is significantly enhanced, particularly concerning water use (often cited as up to 90-95% less than conventional farming) and nutrients, which are delivered directly to the plants in optimized quantities, minimizing waste [22], [23]. The enclosed and controlled environment drastically reduces the need for pesticides and herbicides, leading to cleaner produce [5]. Furthermore, PFs can be located in or near urban centres, shortening supply chains, reducing transportation costs and emissions, and providing consumers with fresher, locally grown food. They also offer the potential to fine-tune growing conditions to enhance specific qualities, such as nutritional value or flavour [4], [24].

### 2.1.3 Current Status and Maturity

PF are to great extend a result of current times, digital disruption is happening in all industries, and agriculture is not an exception, particularly PF are only possible by the unprecedented technology progress in areas such as IoT, light technology, Big Data, telecommunications, automation/robotics, and ML/AI. This disruption, named as the fourth agrarian revolution is characterized by the combination sensors, high-tech construction materials and digital technologies [25]. The PF industry is evolving, moving from first-generation systems focused on basic environmental automation towards second-generation, data-driven facilities aiming for optimization [26]. Figure 2 depicts this maturity curve, emphasizing the shift towards data management, analytics, and automation across the production cycle.

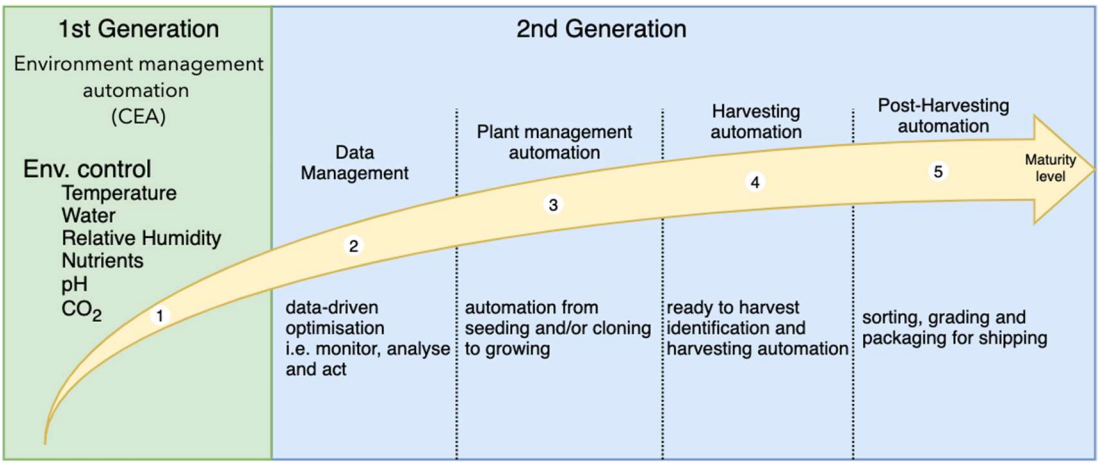



*Figure 2 Plant Factories maturity curve (source [26])*

Currently we are in transition to a second generation of PFs, *i.e.* from environment management automation setup to data-driven optimised and automated Plant Factories. As shown in Figure 2, there is a logical maturity journey in the production automation, starting by using the sensor and actuator capabilities of 1st generation, but moving away from strictly rule base environment control decision making, but instead by enhancing the technological infrastructure, allow broader data collection and analytics, extending the data points to other features that would allow measurement of phenotypic plasticity in function of environment conditions. These capabilities are assigned as maturity level 2, which would allow growers to optimise production in one or more objectives, such as yield, plant metabolites, energy consumption, etc. [26].

This transition is attracting the attention of untraditional players in the agriculture sector, signs of it is the formation of a vibrant digital startup community around this topic, i.e. an increasing and dynamic amount of agrotech startups are being created, coexisting in business ecosystems (*e.g.* device, cloud providers, etc) and with similar capital funding strategies, where most of the investors are coming from digital industry and financial sector. Some high-profile examples are:

- Aerofarms (https://aerofarms.com), more than $400m invested by IKEA, Goldman Sachs, etc [25];
- Plenty (http://www.plenty.ag) more than $400m invested by SoftBank, Eric Schmidt (former Google chairman) and Jeff Bezos (Amazon), etc [25];
- Bowery (https://boweryfarming.com) more than $172m invested by Google Ventures, Dara Khosrowshahi (Uber CEO), etc [25][27][28]

The recent failures highlight the need for robust business models, operational efficiency, and continued technological advancement to ensure long-term sustainability. Critical technological advancements, particularly the development of energy-efficient LEDs with controllable spectrums, have been crucial enablers [29]. LEDs offer significant energy savings (70-85%) and longer lifespans compared to traditional HPS or MH lamps [30], [31], [32], while allowing precise control over light quality known to influence plant growth, morphology, and nutritional content [32], [33], [34], [35].

### 2.1.4 Key Challenges

Despite the promise, significant challenges hinder the widespread adoption of PFs. The high initial capital investment required for construction and technology is a major barrier [5] Operational costs, driven primarily by energy consumption for artificial lighting (LEDs, HPS, MH) and climate control (HVAC), remain substantial [7], [31]. Figure 3 illustrates the significant share of electricity used for lighting and cooling/dehumidification in a typical PFAL [7].

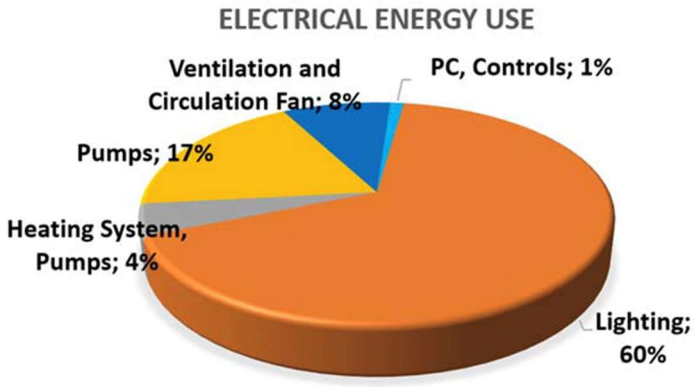



*Figure 3 Electrical energy use in the cultivation chamber (source* [7]*)*

Economic viability is a persistent concern, as highlighted by recent industry struggles and bankruptcies [8], [9], [10], [11], [12], [13], [14]. Competing with lower-cost field-grown produce is difficult, especially for commodity crops. Scalability also presents challenges, as optimizing large-scale facilities requires complex engineering and management. Furthermore, the range of crops economically suitable for PF production is

currently limited, typically focusing on high-value, fast-growing, short-stature plants like leafy greens and herbs [5]. Expanding this range requires further research and optimization.

The bibliography analysed in this section leads to the conclusion that PF are a path forward to produce high quality plant-based food, meeting the new consumer demands, while using sustainable practices. Still, PF technology seems to be experiencing the same initial challenges, such as obstacles and inefficiencies, as most innovative technologies, which are typically resolved as the technology matures. The literature suggests a common understanding that the viability of PF depends on the ability to optimize production. This optimization is only possible through data-driven approaches supported by an IoT ecosystem, which provides both environmental awareness and automated controls. PF optimization relies on facilities design and production processes method, very dependent on technology advancements. In addition, it is important to highlight the potential for knowledge transfer from other industries that use more mature concepts, such as *Industrie* 4.0.

The market clearly shows the inability of Plant Factories (PFs) to deliver on their potential. This is evident from the number of companies that have filed for bankruptcy since 2022, a situation usually justified by macroeconomic impacts on energy costs. Some examples of companies that filed for bankruptcy between 2022 and 2024 include:

- Glowfarms, a Germany founded company ceased operations in December 2022, citing macroeconomic and financial challenges[8].
- Fifth Season: This US-based vertical farming company, known for its robotic harvesting technology, shut down operations in December 2022, also citing funding issues[9].
- Future Crops: This Israeli-Dutch vertical farming company filed for bankruptcy in early 2023, primarily due to high energy costs impacting its profitability.[10]
- Kalera: This US-based vertical farming company, specializing in leafy greens, filed for bankruptcy in April 2023 after struggling with profitability and expansion challenges[11].
- AeroFarms: One of the pioneers and most well-known vertical farming companies, AeroFarms filed for bankruptcy in June 2023, despite significant investment and technological advancements[12].

- AppHarvest: This US-based company, focused on large-scale greenhouse production, filed for bankruptcy in July 2023 due to high debt and operational challenges[13].
- Lakeside Produce: While primarily a greenhouse grower, this Canadian company's bankruptcy in 2023 highlights the challenges faced by controlled environment agriculture operations in general[14].
- Bowery Farming was as a pioneering vertical farming company that grew produce indoors using advanced technology, ceased operations in November 2024 due to financial challenges and market conditions[36].

Several factors contribute to the economic challenges faced by PF companies:

**High Operating Costs**

PFs require significant capital investment to build and operate. Energy costs for lighting, climate control, and other systems are particularly high. This makes it difficult to compete on price with traditional agriculture.

**Overreliance on Venture Capital**

Many vertical farming companies relied heavily on venture capital funding, which has dried up recently. This has left them struggling to secure the necessary financing to continue operations.

**Limited Crop Diversity**

Many PFs focus on high-value crops like leafy greens and herbs. This limited product range can make them vulnerable to market fluctuations and consumer preferences.

**Exaggerated Claims**

Some companies overpromised on the potential of vertical farming, leading to unrealistic expectations and investor disappointment.

**Competition**

PFs face competition from both traditional agriculture and other CEA technologies like greenhouses, which may have lower operating costs.

## 2.2 Environmental Factors and Biological Responses in CEA

Optimizing crop production in PFs requires a deep understanding of how environmental factors influence plant and fungal physiology. This section reviews key parameters and their effects.

### 2.2.1 Plants Cultivation Requirements

#### *2.2.1.1 Light*

Light is fundamental for photosynthesis. Plants utilize Photosynthetically Active Radiation (PAR), primarily blue (400-500 nm) and red (600-700 nm) wavelengths [37]. Blue light influences leaf growth and morphology, while red light is crucial for flowering and extension growth [34], [37]. Green light, once thought ineffective, also plays a role in growth and development [34], [37]. Beyond spectrum, light intensity (measured as PPFD) and photoperiod (duration) are critical. Exceeding the light saturation point offers no benefit [34], [37]. Longer photoperiods can increase biomass even at the same Daily Light Integral (DLI)[38]. Far-red light influences extension growth and flowering, while UV and blue light can promote phytonutrient accumulation but may stunt growth if excessive [39]. LEDs allow precise control over these parameters, enabling optimization for specific growth stages and desired outcomes [31], [34], [38], [40], [41], [42], [43] Pulsed lighting is also being explored for efficiency gains [44]. The effect of different light wavelength is summarised in Table 1.

| **Light Spectrum (Wavelength)** | **Primary Effects on Plant Growth and Development** |
|---|---|
| Blue (400-500 nm) | Primarily influences leaf growth and overall vegetative development.<br>Promotes accumulation of various phytonutrients. |
| Red (600-700 nm) | Crucial for flowering and fruit development.<br>Important for the synthesis of phytochemicals. |
| Green (500-600 nm) | Has an impact on the growth and development of several plants; addition to red/blue LED arrays has a positive impact on leaf growth of lettuce. |
| Far-Red (>700 nm) | Supports overall plant growth and tissue expansion.<br>When combine with red light can influence flowering in some long-day plants when combined with red light. |

| | |
|---|---|
| Ultraviolet (<400 nm) | Can improve the accumulation of certain chemical compounds.<br>In moderate amounts promotes accumulation of various phytonutrients, excessive exposition will stunt plant growth. |

*Table 1 Impact of light spectrum on plants [37], [39], [45]*

#### 2.2.1.2 Temperature & Humidity

Temperature directly affects plant metabolic rates, influencing growth and development with optimal ranges varying by species and growth stage [46], [47], [48], [49], [50], [51]. Humidity impacts transpiration, nutrient uptake, and temperature regulation. Low humidity causes stress, while high humidity increases disease risk (e.g., mold). The optimal relative humidity for maximum plant growth lies within 60-70% [52] for many crops, often using dehumidifiers/humidifiers and ensuring good air circulation. Vapor Pressure Deficit (VPD), the difference between actual and saturation water vapor pressure, is often considered a more accurate indicator of transpiration potential than RH alone [53], [54]. Root-zone temperature also significantly impacts nutrient uptake, growth, and physiology [47], [49], [55], [56], [57].

#### 2.2.1.3 $CO_2$ Enrichment

Carbon dioxide ($CO_2$) is a key raw material, or substrate, for photosynthesis. Plants, being autotrophic organisms, absorb $CO_2$ from the atmosphere. They use the carbon atoms from $CO_2$ to construct glucose ($C_6H_{12}O_6$), a sugar essential for their energy supply and growth. Water ($H_2O$) is also necessary for this process, which is driven by light energy (Figure 4 Photosynthesis ).

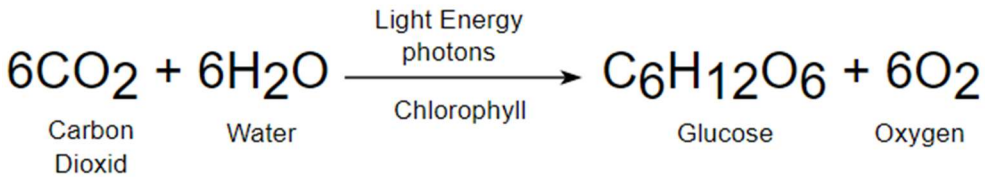



*Figure 4 Photosynthesis equation.*

In enclosed PFs, $CO_2$ can become depleted. In greenhouses, without mechanisms to compensate plant consumption of $CO_2$, the concentration could easily go down to 350 ppm and even lower than 150 ppm during the daytime, which is far from sufficient for optimal crop growth [58]. $CO_2$ enrichment should typically set the $CO_2$ concentration to

800-1500 ppm, depending on crop and stage, accelerating photosynthesis, leading to faster growth and higher yields (15-30% average increase, up to 40-100% for some crops) [41], [59]. $CO_2$ levels and higher light intensity and temperature have positive impact on growth, yield and nutritional composition [60], [58], [59], [61]. $CO_2$ can be supplied via generators or compressed gas tanks, or in combination with adjacent production facilities that emit $CO_2$ such as mushrooms production.

#### 2.2.1.4 Nutrient Delivery

PFs predominantly use soilless cultivation, primarily hydroponics or aeroponics. Techniques include Nutrient Film Technique (NFT), Deep Water Culture (DWC), and Drip Systems. These methods allow precise control over nutrient delivery directly to the roots. Nutrient solutions must contain balanced macro- and micronutrients (N, P, K, Ca, Mg, S, Fe, Mn, Zn, etc.). Solution pH (typically 5.5-6.5) is critical for nutrient availability, and Electrical Conductivity (EC) measures total dissolved salts, indicating overall nutrient concentration [62], [63]. Root zone temperatures are important environmental factors affecting plant growth and yield[64], [65], and it's also notable that pH and EC are temperature-dependent [66]. Adequate oxygenation of the root zone is vital making the solution flow rate a factor that influences root morphology and nutrient uptake [67]. Automated nutrient delivery systems have key role by allowing incorporate strict environmental control to regulate nutrients, pH, electrical conductivity (EC), and temperature to precisely meet specific plant variety and growth stages needs[67].

#### 2.2.1.5 Air Circulation

Air circulation is crucial for crop production due to its multifaceted impact on the growing environment. It simultaneously stabilizes and homogenises temperature and humidity, reduces leaf condensation and phytosanitary risks [68], [69], while also ensuring adequate carbon dioxide supply and oxygen removal for efficient photosynthesis [70], [71]. Proper ventilation is also vital to ensure optimal air conditions for the build-up of volatile organic compounds (VOCs). Plants produce and release these VOCs, which act as key tools for signalling (e.g., attracting pollinators, communicating with other plants and microorganisms) and self-defence (e.g., deterring herbivores and pathogens)[72], [73]. These interconnected benefits underscore the necessity of effective air movement for healthy and productive plant growth.

### 2.2.2 Mushroom Cultivation Requirements

In the context of this thesis, the focus is on commercial fungi cultivated primarily for their reproductive structures, commonly known as fruiting bodies or mushrooms. This scope contrasts with other research areas currently exploring the use of fungi to produce mycelium-based sustainable materials (e.g., construction materials [74]). The solution considered aims to support the production of edible mushrooms such as *Agaricus bisporus* (button/portobello), *Pleurotus spp.* (oyster), and *Lentinula edodes* (shiitake), requiring environmental controls capable of supporting all stages of their lifecycle.

Biologically, unlike plants which are autotrophic, fungi are heterotrophic, meaning they absorb nutrients from organic substrates (e.g., compost, wood, straw). In this context, the commercial value lies in the 'mushroom,' which is the reproductive structure (fruiting body) of the fungus. The main vegetative body is the mycelium, a network of fine, thread-like cells growing unseen within the substrate.

#### *2.2.2.1 Lifecycle Stages in Commercial Cultivation:*

##### 2.2.2.1.1 Spawn run: Colonizing the Substrate

Cultivation typically begins by introducing 'spawn' (mycelium grown on a carrier like grain) into a prepared nutrient-rich substrate. During the spawn run, the mycelium grows and spreads, colonizing the substrate completely. The amount of spawn inoculated significantly affects the colonization duration and, consequently, the time to fruiting.

**Substrate moisture**: should range from 60% to 75%. Below 40%, mycelial growth is slow and wispy. Substrate moisture naturally decreases after inoculation, particularly after the first flush [75]. For example, straw starts near 75% moisture, drops significantly after the first flush to around 60%, and continues to decline [75]. The cultivator's main task during this phase is managing moisture. Limiting moisture loss before initiation is crucial because mushrooms are about 90% water [75]. Maintaining high humidity during spawn run helps retard substrate moisture loss.

**Air flow:** Mushroom mycelium is highly tolerant of carbon dioxide. It thrives at $CO_2$ levels lethal to humans; some Oyster mushroom growth rates peak at 20% (200,000 ppm) [75]. However, high $CO_2$ also stimulates competitor fungi. The optimal $CO_2$ level varies by strain and whether the substrate is pasteurized or sterilized. Introducing fresh air reduces carbon dioxide but increases evaporation, lowers humidity, changes temperature, and introduces more airborne contaminants [75].

**Temperature:** required is generally higher than for primordia formation. Internal substrate temperatures still should not exceed 35° C [75]. Higher temperatures, especially combined with the high $CO_2$ levels of spawn run, can activate black pin molds and other thermophilic competitors [75], [76], [77].

**Lighting:** when moderate has no noticeable effect on mycelium during spawn run while intense light could damage its structures. Mycelial typically becomes photosensitive only after reaching critical mass, usually coinciding with full colonization and a significant drop in carbon dioxide levels. Darkness is generally preferred during colonization [75].

#### 2.2.2.1.2 Primordia Formation: The Initiation Strategy

Primordia formation is also known as the initiation strategy and is the most critical step. It involves adjusting environmental variables to trigger mushroom formation. The key environmental factors are moisture, air exchange, temperature, and light.

**Moisture:** This stage requires direct watering coupled with controlled evaporation to maintain high humidity (95-100%). Fog-like conditions are important when aerial mycelium is first exposed to the growing room environment. Once primordia appear, gradually reducing humidity from 100% to 90-95% is often beneficial. Humidity should be measured in multiple locations in the air space above the colonized substrate [75].

**Air Exchange:** is increased to sharply lower carbon dioxide and provide oxygen($O_2$). CO2 levels should be below 1000 ppm, ideally below 500 ppm, for maximum mushroom formation. Air exchange should be specifically adjusted to achieve the target $CO_2$ levels for each species [75].

**Temperature:** Many strains require a temperature drop or rise to a specific critical plateau to form mushrooms; a temperature drop is needed for most. Since mushroom formation is primarily a surface phenomenon, the growing room atmosphere must be altered to affect the substrate temperature. Mycelial colonization generates heat, and after full colonization, heat generation lessens, and internal substrate temperature naturally approaches air temperature[76]. This is the ideal time to align other factors for mushroom formation. The temperature thresholds listed in Table 2 for each species refer to the substrate ("bed") temperature. Air temperature is adjusted to achieve the desired change in substrate temperature. A lag time, often 24-72 hours, occurs after changing air temperature before the substrate temperature adjusts[75], [76], [78]. The critical

temperature plateau is usually within the top 5-10 cm of the substrate surface, where primordia form.

**Light:** influences stem elongation and cap development. Ideal light intensity and wavelength vary by species and strain. Specific photoperiods and spectral frequencies are not established for all species. For most species, light levels between 50-1000 lux and wavelengths of 380-480 nanometres (green to blue) appear most stimulatory for primordia formation[79].

#### 2.2.2.1.3 Fruit body (Mushroom) development

In this stage pins rapidly develop and enlarge into the recognizable mushroom shape, this shift to fruiting seems to be trigger by nutrient deprivation, defined as a sudden lack of food. This stage requires careful control over humidity (still high, but sometimes slightly lower than pinning), temperature, and fresh air exchange to ensure mushrooms grow to the desired size and quality before they mature and release spores. Harvesting occurs during this stage.

**Moisture:** Atmospheric moisture must be carefully managed to support mushroom development without favouring competitors. Relative humidity approaches 100% during primordia formation but should be lowered to allow a constant evaporation rate from the fruitbodies. The crop should be sprayed several times daily, provided excess water is quickly absorbed by the mushrooms, substrate, or air. This dynamic moisture balance encourages the best crops. Reducing humidity several hours before harvesting can extend shelf life [75].

**Air Exchange:** Air exchange and turbulence are managed to maximize benefits for the mushrooms by reducing carbon dioxide, increasing oxygen, and facilitating constant evaporation from the maturing mushrooms [75].

**Temperature:** typically remain constant or are raised after primordia formation. Temperature primarily controls the speed of fruitbody development. Warmer temperatures result in faster growth, while colder temperatures slow it down. Fruiting at cooler temperatures can yield firmer, higher-quality mushrooms at harvest [80][81].

**Lighting:** Adequate light is necessary a relevant environment factor in mushroom cultivation. Insufficient light can cause significant development problems, such as stem elongation and cap malformation, especially in common light-sensitive species such as Oyster and Enoki. Beyond influencing mushroom's physical shape. light intensity also

affects pigmentation. In some strains of Oyster mushrooms, for example, brighter light leads to a darker coloration, while other strains react by becoming paler.[79]. This response is also influenced by temperature[79].

**Number of harvests and duration** depends on the strain and process. With Shiitake on sterilized sawdust/chips/bran, 4 or 5 crops are typical [75]. For Oyster mushrooms grown in columns on pasteurized straw, two to three flushes are usually most efficient. Approximately seven days to two weeks separate the end of the first flush from the start of the second. Fruiting occurs within specific "windows of opportunity" A period of dormancy is needed between crops for the mycelium to accumulate nutrients for the next flush [75].. During these windows, the cultivator must actively signal the mycelium with as many environmental stimuli as possible. Synchronizing these conditions should lead to the best possible fruiting.

#### 2.2.2.1.4 Sporulation

If left to fully mature, the fruiting body will produce and release microscopic spores (usually from gills or pores) to propagate the fungus naturally. In commercial settings, mushrooms are typically harvested before heavy sporulation to maximize quality, yield, and shelf life.

In summary, successful commercial mushroom production hinges on the precise management of multiple, interacting environmental variables. Factors such as substrate moisture, relative humidity, air exchange (specifically controlling $CO_2$ and $O_2$ levels), temperature, and light must be carefully controlled. Crucially, the optimal settings for these parameters are not fixed; they vary significantly depending on both the specific mushroom variety being cultivated and its current developmental stage (e.g., spawn run, pinning, or fruitbody development). Achieving high yields and quality requires a dynamic, multi-dimensional approach to environmental control tailored to these specific needs. Table 2 provides examples of optimal condition for a few most common commercial mushrooms.

| Mushroom | Stage | Temperature ,(°C) | Humidity (%) | $CO_2$ (ppm) | Lighting (lux) |
|---|---|---|---|---|---|
| Pink Oyster | Spawn Run | 24-30 | 95-100 | >5,000 | n/a |
| | Primordia Formation | 18-25 | 95-100 | 500-1,000 | 750-1,500 |
| | Fruiting | 20-30 | 85-90 | 500-1,500 | 750-1,500 |
| Lion's Mane | Spawn Run | 21-24 | 95-100 | 5,000-40,000 | n/a |
| | Primordia Formation | 10-15.6 | 95-100 | 500-700 | 500-1,000 |
| | Fruiting | 18-24 | 85-95 | 500-1,000 | 500-1,000 |
| Chestnut | Spawn Run | 21-24 | 95-100 | >10,000 | n/a |
| | Primordia Formation | 10-16 | 98-100 | 1,000-2,000 | 100-200 |
| | Fruiting | 10-16 | 90-95 | 1,000-5,000 | 100-200 |
| King Oyster | Spawn Run | 24 | 90-95 | 5,000-20,000 | n/a |
| | Primordia Formation | 10-15 | 95-100 | 500-1,000 | 500-1,000 |
| | Fruiting | 15-21 | 85-90 | <2000 | 500-1,000 |
| Shiitake | Spawn Run | 21-27 | 95-100 | >10,000 | 50-100 |
| | Primordia Formation | 10-16 | 95-100 | <1,000 | 500-2,000 |
| | Fruiting | 16-18 | 60-80 | <1,000 | 500-2,000 |
| Maitake | Spawn Run | 21-24 | 95 | 20,000-40,000 | n/a |
| | Primordia Formation | 10-15.6 | 95 | 2,000-5,000 | 100-500 |
| | Fruiting | 13-16 | 75-85 | <1,000 | 500-1,000 |

*Table 2 Fungi's optimal environment conditions [75]*

### 2.2.3 Fungi and Plant Symbiotic relation

The ubiquitous association between plants and fungi, particularly exemplified by mycorrhizal symbioses, represents a fundamental ecological interaction with profound implications for nutrient cycling and ecosystem dynamics. This mutualistic partnership is predicated on the reciprocal exchange of key resources, highlighting the contrasting metabolic capabilities and adaptive strategies of these two kingdoms[82].

Plants, as photoautotrophic organisms, possess the unique capacity for photosynthetic carbon fixation. This intricate biochemical process, driven by chlorophyll pigmentation within chloroplasts, enables the conversion of atmospheric carbon dioxide ($CO_2$) and water ($H_2O$) into energy-rich carbohydrates ($C_6H_{12}O_6$), effectively establishing them as primary producers within terrestrial ecosystems[83]. The stoichiometry of this reaction is represented by the following equation:

$$CO_2 + 6H_2O + Light\ Energy\ (photons) \rightarrow C_6H_{12}O_6 + 6O_2$$

In opposition to plants, fungi are heterotrophic organisms, lacking the photosynthetic machinery necessary for autotrophic carbon assimilation. They rely on the acquisition of organic carbon from external sources to meet their metabolic demands. Mycorrhizal fungi have evolved specialized hyphal structures that facilitate the colonization of plant root systems, establishing an intimate interface for resource exchange[84][85].

This symbiotic association enables the fungi to access plant-derived carbohydrates, primarily in the form of glucose, translocated from photosynthetically active tissues to the roots. In reciprocation, the extensive hyphal networks of mycorrhizal fungi effectively expand the explorative capacity of the plant root system, increasing the absorptive surface area for the acquisition of essential nutrients, such as phosphorus (P), nitrogen (N), and micronutrients. These nutrients, often limiting in terrestrial environments, are translocated to the plant host, promoting growth, development, and stress tolerance. The metabolic dichotomy between plants and fungi is further underscored by their respective respiratory pathways [86][87]:

- Plants (Photoautotrophs): Primarily utilize carbohydrates generated through photosynthesis for cellular respiration, generating ATP and metabolic intermediates.

- Fungi (Heterotrophs): Utilize organic carbon sources, such as plant-derived carbohydrates, to fuel cellular respiration, generating chemical energy (ATP) through the oxidation of glucose:

$$C_6H_{12}O_6 + 6O_2 \rightarrow CO_2 + 6H_2O + Chemical\ Energy\ (ATP)$$

The plant-fungal symbiosis, therefore, represents a finely tuned biogeochemical cycle (see Figure 5), whereby carbon flows from photoautotrophic plants to heterotrophic fungi, while essential nutrients are translocated from the soil matrix to the plants via the fungal hyphae. This intricate interplay expresses the ecological significance of plant-fungal interactions in maintaining nutrient cycles, promoting plant productivity, and shaping community structure within terrestrial ecosystems.

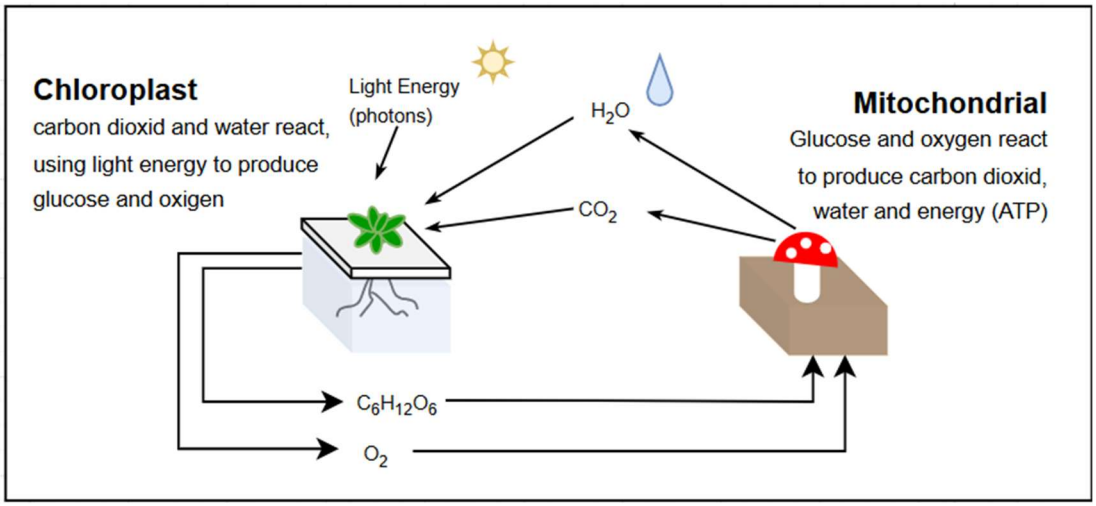



*Figure 5 Autotrophic and heterotrophic symbiotic cycle.*

## 2.3 Control Theory in Plant Factories

PF should be understood as a system designed to stablish stable and optimal environment conditions along the production cycle of a given crop. The implementation of optimal production processes in PF is highly complex, as a system that requires to embody the diversity of non-linear relations between environment conditions, and between these and phenotypical responses specific to each genotype. The representation of these relations is expressed as production recipes and used to schedule environment's set points throughout the crop production cycle.

### 2.3.1 Open-loop control architecture

A simple approach to set a production recipe into an environment would be to implement of an open-loop controller as portrayed in Figure 6. In this approach, the environment state signal ($S_o$) is stablished through a set of stateless rules reversed engineered from the physical system and specified declaratively in the Control Law, that set the actuations (b) required to achieve a $S_o$ that would converge to the intended reference state signal $S_r$.

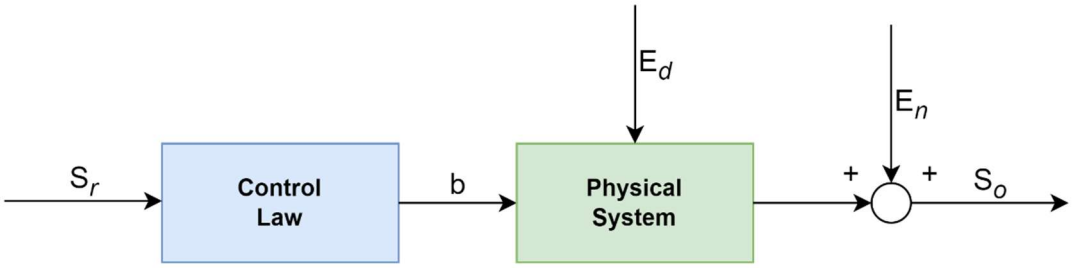



*Figure 6* ***An open-loop control architecture****. In this system, the control action is independent of the process output, as there is no feedback loop to correct for errors. The variables are defined as: $S_r$ is the reference signal, b is the control signal, $E_d$ represents external disturbances, $E_n$ is measurement noise, and $S_o$ is the final system output.*

This approach assumes the dynamics of the physical system of interest is immutable and fully representable in the form of stateless rules, and when whenever acted upon, the outcomes are deterministic and exempt of any external disturbances. Plant factories however do not conform with these assumptions since these systems that are characterised for:

- **Uncertainty**, both from the perspective of the physical environment and crop response to environment's inputs. Crops are inherently complex, where physical-chemical functions at the cellular and molecular level form extensive interaction networks that govern input responses that are almost always non-linear [88], e.g., temperature effect on plant's nutrients uptake, growth, physiology and accumulation of compounds[89][47][57] or the double interactions between N, P, K, S, Zn, and Fe have in plants at the physiological level, are still poorly understood[90][91]. Therefore, from crop production point of view and even assuming full control of input factors, there uncertainties resulting both from incomplete information and lack of ability to model phenotypic response subject to complex feature relations in a high dimensional space. Additionally, another factor of uncertainty result from exogenous disturbances, difficult to predict and/or model (e.g., air breaches, asset performance degradation or critical failures, etc).

- **Instability**, from the perspective of ensuring the intended output state signal ($S_o = S_r$) is constantly being challenged through different factors, being those from unpredicted events, from architectural components and production systems (e.g., temperature generated by lightning, operating machinery, etc). Other important factor constantly generating instability is the fact that PF produce living organisms, which through the photosynthesis, consume environment's resources (e.g., $CO_2$, nutrients, etc) and as result of underlying phytobiological process, i.e., photosynthesis, introduce changes into the environment (e.g., RH%/evapotranspiration, $CO_2$ concentration, water's nutrient availability, etc). These impacts vary considerably through the day (day/night cycle) and along the specific crop and its lifecycle[92].

- **Efficient control.** PF is all about overcoming external effects and optimization of a state or output with respect of a cost, by applying into the system the precise quantity of inputs at the precise moment [93].

In summary, plant factories justify the need of sensor-based closed-loop feedback control systems that continuously monitor the environment and dynamically adjust set points to achieve the desired state.

### 2.3.2 Closed-loop feedback control

In the closed-loop feedback control (Figure 7), the environment state represented by the output signal ($S_0$) is sensed and subtracted from the reference signal ($S_r$), obtaining the error (ε). This error then is considered by the control law to specify the actuation (b) being applied to the physical system. As consequence the physical environment state is subject state change due to action(s) (b) but not limited. The effects on the physical environment could reflect the dynamic nature of casual loop, i.e. environment state affect crops metabolism and vegetative cycle which will then affect environment state. Additionally, the physical system is subject to external disturbances ($E_d$). Then the new state is sensed and fed back to the next iteration. This feedback loop mechanism is generally able to stabilize the unstable dynamics of the physical system, while correcting externa disturbances ($E_d$) and filtering the noise ($E_n$) in the output signal.

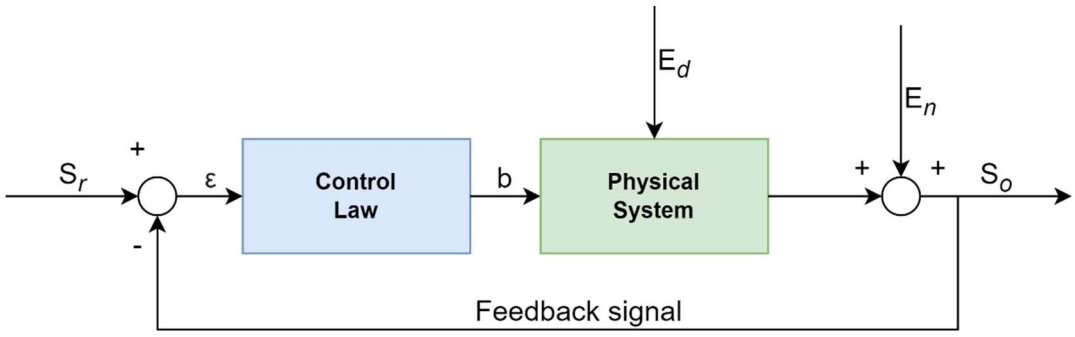



*Figure 7* ***Closed-loop feedback control architecture.*** *The diagram shows how a controller adjusts the output of a physical system. The system works to minimize the error (ϵ) between the reference signal ($S_r$) and the measured output. The variables are defined as follows: $S_r$ is the reference signal (or setpoint), ϵ is the error signal, b is the control signal, $E_d$ is the external disturbance, $E_n$ is the measurement noise, and $S_o$ is the final system output.*

In this framework it is considered an input-output coupled system of ordinary differential equations (ODE) in terms of the $a \in \mathbb{R}^{N_a}$ state of the system, where $N_a$ is the dimension of the state.

$$\frac{d}{dt}a = F(a, b, E_d),$$
$$S_o = G(a, b, E_n),$$

The actuation is applied the system is given by $b = \mathbb{R}^{N_b}$, where $N_b$ is the actuators dimension. Actuation $b$ and external disturbances $E_d$ directly affect the physical system, measured as output signal $S_o \in \mathbb{R}^{N_o}$, where $N_o$ is the dimension measurements. $S_o$ is expected to be a nonlinear function of state a, actuation $b$ and noise $E_n$. To guarantee the desired system's stability, noise attenuation, external disturbances and convergence to the reference signal, the actuation $b$ is generally constructed as:

$$b = K(S_r, S_o)$$

Additionally, the feedback loop control framework mechanism could promote different control/optimization objectives, reflected in a cost function $J$, which depend on state $a$ and the actuation $b$, i.e. $J(a, b)$. The cost function can be formulated as the summation of cost of the system being in state $a$ , i.e., $J_a$ and the cost of actuation $J_b$. Therefore, the simplified cost function could be:

$$J(a, b) = J_a + \gamma J_b$$

Where $\gamma$ works as a penalization parameter to allow to balance the prioritization of actuation cost (high $\gamma$) or state cost (low $\gamma$). Multiple optimization objectives can be added to the function, by adding the relevant transfer costs from input to output.

Finally, the physical system could be modelled through machine learning techniques to produce the control law and embedding the optimization objective(s) defined in the cost function.

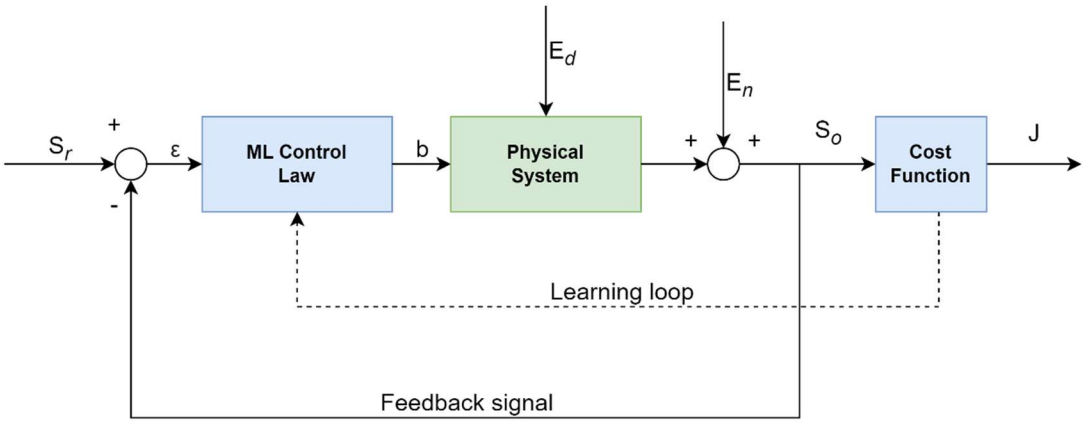



*Figure 8* ***A closed-loop feedback control architecture with cost optimization.*** *This system employs a machine learning (ML) control law that is refined through a learning loop based on a cost function, J. The primary variables are the reference signal, $S_r$; error, $\epsilon$; control signal, b; external disturbance, $E_d$; measurement noise, $E_n$; and the system output, $S_o$.*

As depicted in Figure 8, the environment state $S_o$ is captured and corresponding variable(s) used to compute the cost. The calculated cost is then used as learning loop to update the ML Control Law, which besides containing the input-output mapping required to $S_o \rightarrow S_r$, it prescribes the actuation subject to the optimization objective(s) considered in the cost function.

### 2.3.3 ML Control Law

Given the infinite possible PF configurations in terms of space and installed technology, as well as the different operating conditions depending on crop and optimization objective, it makes unfeasible to reverse engineer the physical system into discrete logic rules. Machine Learning presents a practical strategy to uncover in a dynamic environment the relation between action and resulting environment state. Still of prime importance to model the mapping of state space with the phenotypic response throughout the crop cycle. These complex relations between control variables and crop response are still not entirely understood[93][94][95]. Applying ML to unveil these relations as part of the closed loop mechanism has its limitations as it requires not only a vast amount of data to train the models, but also the biofeedback that is only observed and measured after a considerable time from the moment the actuation took place, and subsequently the desired state was realized[93]. As result, it is desirable to combine ML

with mechanistic and physiological plant growth models (MPMs). Some of examples of MPMs software packages are CropSyst [96], VegSyst[97], BioCro II [98], still seem in a very early development stage which is likely to mature as PF factories mature, benefiting from enormous amount of the data it produces, likely to allow to create digital twins of a variety of crops.

## 2.4 Digital platforms for Industry

The current subsection intends to provide a literature review on existing mainstream architecture frameworks for Industry Internet of Things (IIoT) systems, current maturity adoption in PFs and possible transfer of *Industrie 4.0* concepts and standards.

*Industrie 4.0*, often called the Fourth Industrial Revolution, represents a profound technological shift in manufacturing and industrial production. At its core, this concept aims to achieve higher levels of productivity and efficiency, accomplished through process automation, workflow optimization, and the power of real-time monitoring and data analysis, all contributing to increased output and reduced waste. Additionally, a significant goal is to create greater flexibility and agility within production systems. Smart factories are designed to be inherently adaptable, allowing businesses to quickly adjust production in response to changing demands and market shifts [19], [99]. These capabilities are made possible by key emerging technologies, including [100], [101], [102]:

- Industrial Internet of Things (IIoT): Connecting devices, sensors, and machines to collect and exchange data in real-time.
- Cyber-Physical Systems (CPS): Systems that integrate computational and physical components, enabling monitoring and control of physical processes through software and networks.
- Cloud Computing: enables scalable and flexible computing resources for data storage, processing, and application hosting.
- Big Data and Analytics: Collecting, analysing, and interpreting vast amounts of data generated by connected systems to gain insights and optimize operations.
- Artificial Intelligence (AI) and Machine Learning (ML): Enabling systems to learn from data, make intelligent decisions, and automate complex tasks.
- Advanced Robotics: Collaborative robots and highly automated systems working alongside humans.
- Additive Manufacturing (3D Printing): Enabling on-demand production and customization.
- Augmented Reality (AR): Enhancing human capabilities through overlaying digital information onto the physical world.

Some industries such and Automative [103], Logistics [104], Energy [105] and life sciences [106] have widely implemented the technology-driven *Industrie 4.0*, with some companies already transitioning to the value-driven and human-machine collaboration evolutionary stage of Industry 5.0[107], [108].

Plant factory industry is still in an early phase, specially from technological perspective [15] which is still to be fully established[109]. The current landscape is characterised by a diversity of architectures and technologies created in-house by growers, introduced by start-ups companies aiming to provide services to PFs or adapted and introduced by suppliers traditionally operating in other industries. This results on a heterogeneity of implementations and lack of standards, common in a maturing paradigm, result on higher investment requirements and associated risk. Standards should be part of the innovation process [16][17], as means for an agile and fast technological adoption, producing highly modular solutions, and facilitating an innovation ecosystem, e.g. multi-vendor production systems [18]. Standardisation of architectures, data formats, semantics (often defined through vocabularies, taxonomies, and ontologies), and interfaces is key to creating interoperability, a critical element in modern industrial internet of things (IIoT) systems in general, and PFs in particular.

The rationale can be summarized as follows:

- Modern industrial systems are made of interoperable parts. Lack of standards would require that these parts have greater built-in common capabilities and/or custom-made interfaces, creating an unmanageable complexity resulting on high cost of ownership and low system flexibility, maintainability, and resilience.
- PF like smart manufacturing is all about production optimization through integration and automating all aspects of the value-chain, making essential that Information Technology (IT) and Operational Technology (OT) work together, something only possible if each component of the architecture is compatible with common data formats, communication, and security protocols.
- Standards enforcement avoids vendor lock-in, encouraging a competitive setting and the creation of a technological ecosystem, likely resulting on faster pace of innovation, adoption and lowering costs.
- The integration of IIoT systems introduces significant complexity and heterogeneity in systems, technology, and data, resulting in increased security

risks [110] that can easily propagate throughout the entire production system, a core component of business operations.

### 2.4.1 Design Principles

Plant factories share the same challenges and opportunities as any other industry that is digitising their production processes. To great extend could be seen as one more industry as smart manufacturing fitting perfectly in the *Industrie 4.0* concept and therefore, requiring, at least at high level, the same design principles. The commonly accepted design principles for *Industrie 4.0* (Figure 9) are[20], [99], [111]:

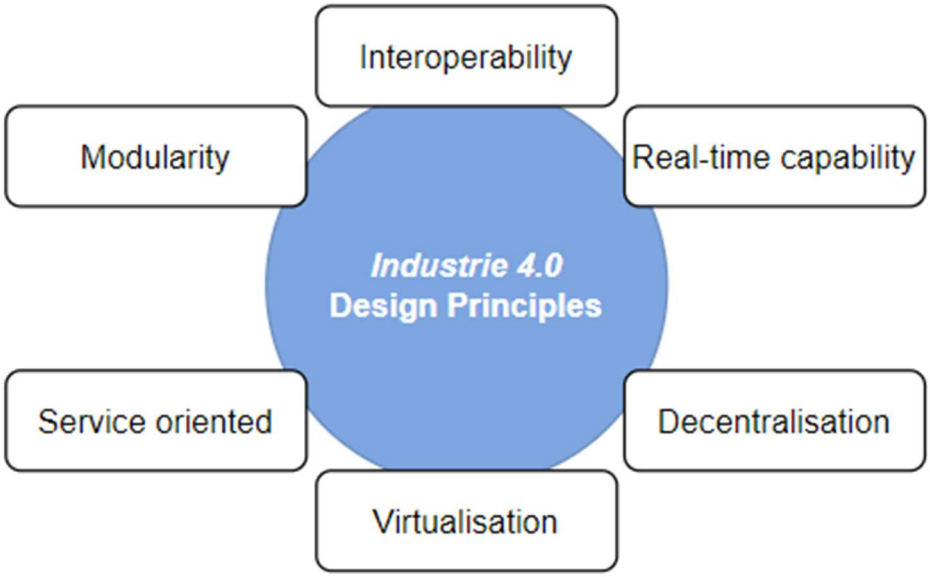



*Figure 9 Industrie 4.0 Design Principles (adapted from* [20], [23], [99], [111])

***Interoperability***, the ability that all elements of the system, such as devices, sensors, machines, and people to interconnect as a collaborative ecosystem [20], [23], [99], [111].

***Real-Time Capability***, perpetual connectivity offers continuous data capture as it is produced by the different elements participating in the system, allowing continuous monitoring, real-time analytics and, fast and automated decision making, e.g., the ability to detect system anomalies, anticipate failures and apply mitigation actions such as opportunistic maintenance scheduling. [20], [23], [99], [111] Additionally, this capability must provide flexibility and dynamic optimization of production system.

***Virtualisation***: implementation of Cyber Physical Systems (CPS) which integrate sensing, computation, control and networking into physical objects, infrastructure, and people, connected through the Internet [19] and flowing vast amounts of data, resulting on the of a digital copy of the physical world. Additionally, CPSs must also be able to monitor objects existing in the surrounding environment and therefore provide the ability to create a virtual copy of everything. CPSs in essence allow for a time and space representation of all objects in the system, providing transparency to the current and past state of the system, as well allowing to simulate future state scenarios. These virtual copies, known as Digital Twins, can be defined as "[…] a dynamic and self-evolving digital/virtual model or simulation of a real-life subject or object (part, machine, process, human, etc.) representing the exact state of its physical twin at any given point of time via exchanging the real-time data as well as keeping the historical data. It is not just the Digital Twin which mimics its physical twin but any changes in the Digital Twin are mimicked by the physical twin too." [112].

***Decentralization***: is the ability of CPSs to work independently, deciding autonomously and in real-time, still constrained by the organisation goals. This would require embedded computers, so CPS interact with their environment by sensors and actuators [20], [23], [99], [111].

***Service-Orientation***: in *Industrie 4.0*, the role of humans' shifts from operators of machinery to decision-makers[99]. The increasing complexity of production, where CPS form complex networks and with decentralized delegation of decisions, humans need to have service-oriented systems, which aggregate and present information in a comprehensive fashion to assist humans along decision making process. Additionally, production must be customer-oriented, and therefore consumers must be able to connect through the Internet of Services and set their products specification which in turn can be seamless integrated with the business and operations process [20], [23], [99], [111].

***Modularity***: due to increasingly dynamic marketplaces, customer preferences and emergence of new technologies and materials, it critical that factories can in agile manner adapt the production process to meet new market demands. Both system design strategies and the adoption of standards are critical to enable modular integration machinery from different vendors [20], [23], [99], [111].

The complexity set by these design principles and intrinsic to IIoT system requires a reference framework to capture and structure industry stakeholders' requirements allowing to implement an open, repeatable, functional, and modular architecture. The resulting open platform should support IoT, Big Data and Artificial Intelligence technologies, understood as the enablers that would drive sustainability, productivity, lower costs, and streamlined operations[113], [114], [115].

### 2.4.2 Industrial IoT reference frameworks

Several ongoing efforts to define IIoT reference frameworks, funded and lead by consortiums of governments and private organizations, being the two main examples Platform *Industrie 4.0* and Industrial Internet consortium.

#### *2.4.2.1 Platform Industrie 4.0 [116]*

Launched in Hanover Fair 2013, is steered and led by the German federal government, has the goal to promote the development of I4.0, actively supported by 350 stakeholders from over 150 organizations, including politics, business, science, associations, and trade unions. As result, from this initiative it was produced a solution-neutral reference architectural framework for industry digitalization (Figure 10), named *Reference Architectural Model Industrie 4.0* (RAMI 4.0).

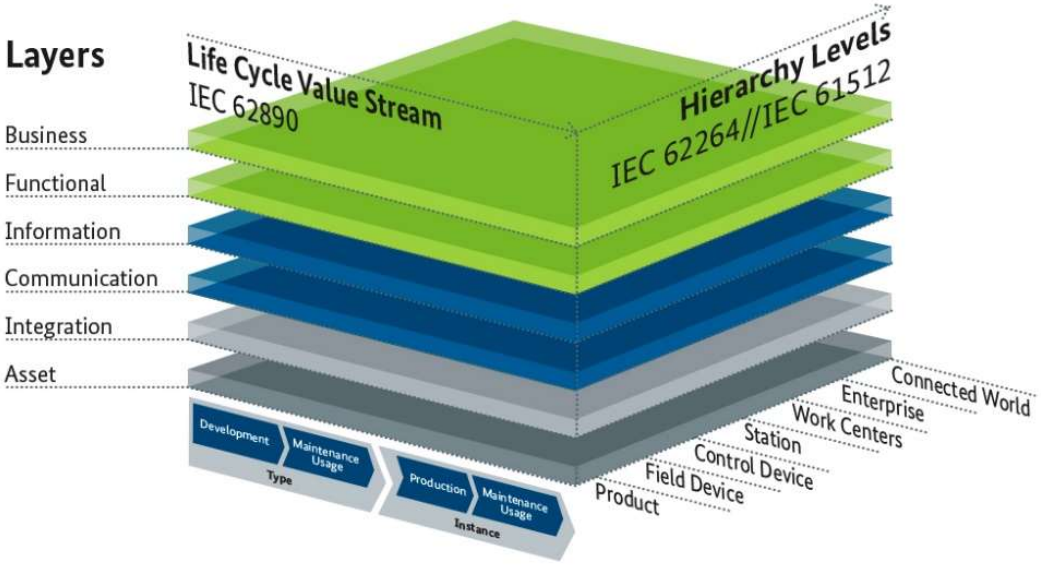



*Figure 10 RAMI 4.0 © Platform Industrie 4.0, ZVEI* [117]

Adapted from Smart Grid Architecture Model (SGAM), RAMI 4.0 describes the I4.0 space in a three-dimensional model[117]:

- **Life Cycle and Value Stream**, describes the product/system life cycle, defined as Type and Instance. Type comprehends steps of opportunity identification, development, testing, and production prototype. After a Type is complete, when is delivered and deployed, it becomes an instance of it in the production environment. The instance could be adjusted, improved, etc, changing to Type and Instance several times. In essence this dimension represents the product life cycle from ideation to decommission and the in-between iterative nature. Additionally, the ability to connect this process with relevant information from all networked elements (people, objects, and systems) participating in the value creation process, allowing to dynamically determine the optimal value stream at any given point in time, based on different criteria such as cost, availability, and resource consumption. In essence all elements in I4.0, such as parts, machines, factory, orders and products have a lifecycle, and on top of its orchestration is required to generate the value stream.

- **Hierarchy Levels** describes the different functional assignments within a plant or factory, as per International Electrotechnical Commission series of norms IEC 61512, IEC 62264:2013, addressing the terminology, physical model, and the enterprise-control system integration. The hierarchy levels are enhanced to support I4.0, i.e., on top of it, the plant or factory extend the reach to the "Connected World" and by the other hand recognise the relevance of new generation smart devices represented by Filed Device and Products, under the Control Device. In summary the layers considered are:
    - *Connected World*, representing the relationship between one or a group of assets or entities with external world.
    - *Enterprise*, representing the business organization which could be one or a collection of business entities responsible for determining business goals, how to achieve them and resulting orchestrating.
    - *Work Centres,* representing highest level element that performs manufacturing functions, are considered in the production planning and

scheduling. Characterized for having well defined capabilities and capacity e.g. production unit, production line, storage area, process cell, etc. Work Centres group one or more Stations (aka Work Units) cascading down the planning and scheduling to them.

- *Station*, or Work Units are the lower-level elements that perform manufacturing functions, and the lower-level elements considered in the planning and scheduling. Have specialised capabilities within the Work Centres and are composed by lower-level equipment units that are subject to the cascade manufacturing execution resulting from planning and scheduling stablished by the upper hierarchical levels.
- *Control Device*, representing the logical control (e.g., programmable logic controller) of field devices.
- *Field Device*, representing the physical device at the field level, interacting directly with manufacturing process and the products being produced (e.g., smart sensor).
- *Product*, representing the product being produced.

- **Layers**, provides an abstract representation of different elements in I4.0's information technology (IT) landscape and respective interoperability. Each layer plays a specific role in the overall system architecture, from organization and business processes (Business layer) down to the "things" in the physical world (Asset layer). The layers are structured as follows:
  - ***Business Layer*** ensures the integrity of end-to-end value stream, by mapping business models, overall processes and rules, regulatory and legal frameworks. Business integrity and consistency is ensured by linking different business processes and orchestration of services in the Functional Layer.
  - ***Functional Layer*** provides formal description of functions, modelling, and runtime environment for services to support the business layer. Business rules and decision-making logic are authored inside this layer and depending on the scenario can be executed in the lower layers. Designated layer for remote access and horizontal integration to ensure information integrity and process integration consistency.

- ***Information Layer*** provides formal description of rules and data lifecycle management services. It contains runtime environment for ingestion, event processing, enrichment, transformation, integrity, storage, provision of all relevant data generated or consumed by the IIOT system. Conforms the data and makes it in compatible format to be consumed by the Functional Layer. In essence this layer is responsible for collecting data, converting it into information and subsequently supporting the production of knowledge in the organization. The technical implementation can be supported by a variety of standards and modelling methods and tools such as IEC Common Data Dictionary (IEC 61360 Series/ISO13584-42), eCl@ss (https://www.eclass.eu), Standard for the Exchange of Product model data (STEP), Systems Modelling Language (SysML), and AutomationML.
- ***Communication Layer***, enforce a standard and uniform communication through protocols and data formats, ensuring seamless flow of data from and to the Information Layer. The standard adopted by the industry is predominantly the Open Platform Communications – Unified Architecture (OPC-UA) [118][119][120]. OPC-UA over Message Queuing Telemetry Transport (MQTT) is becoming the norm for IoT edge-to-cloud integration being adopted by all major IoT vendors such as AWS, Google Cloud, IBM, Microsoft, SAP and SIEMENS[121]. OPC-UA, identified internationally as standard IEC 62541, is a collection of specifications that define the interface between Clients and Servers, Servers and Servers, respective access to real-time data, historian data, monitoring alarms and events, and other applications[122], i.e., specification to enable interoperability for secure and reliable exchange of data.
- ***Integration Layer***, stablish the transition from the physical and digital domain, contains representation of process related functions of physical assets, related control actions and reporting back the events the digital realm. This layer comprehends elements connected to IT, such as asset documentation, software and firmware, sensors, Human Machine Interfaces (HMI). Each relevant event in the physical world is captured

by the Integration Layer and when applicable generate events in the Information Layer through the Communication Layer.

- Asset Layer is the physical world, i.e., the physical asset instance represented digitally by all upper layers. An asset could be a machinery part, equipment, human, etc.

#### 2.4.2.2 *Industrial Internet Reference [123]*

Published by the Industrial Internet Consortium (IIC), "The Industrial Internet of Things Volume G1: Reference Architecture", is a technical report that describes the Industrial Internet Reference Architecture (IIRA) for IIOT systems. It includes an Industrial Internet Architecture Framework (IIAF) based on ISO 'ISO/IEC/IEEE 42010:2011'[124], providing conventions, principles, and practices to guide the development, documentation, communication, and deployment of IIoT systems. [124]. The IIRA provides a generic architecture description and structure, meant to be used as template, with focus on interoperability, facilitates the mapping of applicable technologies, while guiding the technological and standard development. It aims to provide a common approach for architecture design allowing systematic and consistent architectural implementations, across use cases and industries.

IIAF is structured in viewpoints (Figure 11) providing a comprehensive perspective of considerations in defining and implementing a IIOT system. This viewpoint structure, contextualized in product lifecycle context, provides a top-down approach on defining the IIoT system, guided by the business vision, which defines how it would be used, what are the functional attributes supporting it and finally how it is implemented. The framework contemplates the iterative nature assuming a continuous bottom-up validation and revision of upper viewpoints' assumptions and definitions. In opposition with RAMI4.0's in-depth focus on manufacturing, IIRA approaches IIoT systems across industries, and therefore malleable to each industry and use case specificities.

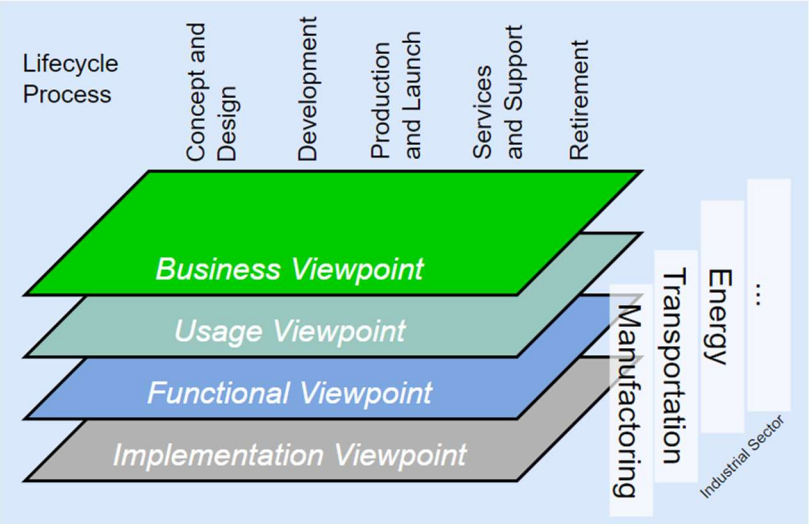



*Figure 11 IIRA Viewpoints (source* [124]*)*

A brief description of each viewpoint:

- ***Business viewpoint*** outlines the future state to be achieved by IIoT system and the resulting value. This is formulated as the organization or industry vision, set of values and quantifiable key objectives, enabled by the IIoT system, and there shaping it together with any business and regulatory constraints. This viewpoint, technically and architecturally agnostic, aims to provide the fundamental capabilities the system must meet so key objectives attainable.
- ***Usage viewpoint***, outlines how the fundamental capabilities identified by the Business viewpoint, will be practised by system's users. This viewpoint is the starting point for systems requirements definition, providing guidance along the entire IIoT system lifecycle, i.e., design, development, deployment, maintenance (corrective and evolutive) and decommission.
- ***Functional viewpoint*** defines the functional capabilities, structure and components required to comply with the usage viewpoint. This architectural viewpoint decomposes the typical IIoT system into building block domains (Figure 12):

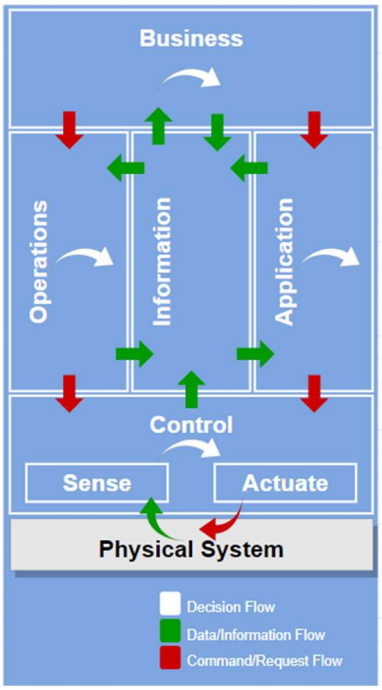



*Figure 12 Functional Viewpoints' domains (source* [124]*)*

- **Control Domain** is the functional domain that implements the Industrial control system (ICS), is responsible for exercising the control of the physical system, through fine grain closed loops reading data from the sensor and applying actuation rules. This domain has the highest data resolution and shortest temporal cycles.
- **Operations Domain** is the functional domain responsible for management and operation of Control domain and all associated functions, such as provision, management and optimization of the control system, which in turn controls the physical system. This domain comprises functions to realise Business functionalities, such as optimisation of operations across asset types and across the value chain. Therefore, the functions considered in this domain are not restricted to asset management, provisioning and deployment but also include asset performance monitoring, predictive and prescriptive capabilities to maximize things like performance, availability, and quality, e.g., pursuing the maximization of overall equipment effectiveness (OEE), resource optimization, etc.

- **Information Domain** is the functional domain responsible for managing and process data. Contain a collection of functions to implement data lifecycle and governance, such as data ingestion, data quality, semantic and syntactical transformation, storage, distribution, access. Additionally, this domain contains functions for data modelling, business intelligence and advanced analytics with possibility of implementing advanced data processing techniques such as streaming analytics. New intelligence is produced in this domain, e.g., in the form data augmentation, inferences or other analytic models and made available for consumption to Business, Operations and Application domains.
- **Application Domain** contains application logic to realise Business domain functionality. This logic has high order of granularity to support for overall business optimisation. Low level continuous operation logic is delegated to the control domain, where local rules and models are maintained for system resiliency in the event of communication loss. Application domain requests to the control can occur as a mean to report on activities progress or operational rules compliance validation. This functional domain subdivided in *Logic & Rules*, which implements logic to support specific application functionalities, and *API & UI* which are functions that expose functionalities through application programming interfaces or user interfaces, to respectively implement integration between applications or human interaction with applications.
- **Business Domain** implements business logic to supporting business processes and related activities. The integration of this domain with IIoT system is what will provide operational transparency to business while enabling streamline of processes and value chain optimization. Example of systems that fall into this domain are Enterprise Resource Planning (ERP), Supply Chain Management (SCM), and Customer Relationship Management (CRM), Asset Management System (AMS), Product Lifecycle Management (PLM), Manufacturing Execution System (MES), Billing and Planning systems.

- ***Implementation viewpoint*** defines the aspects related to the IIoT system implementation that realizes the required set of capabilities scoped by Usage and Functional viewpoint. Stablishes the IIoT architecture, defining its structure, distribution of components and topology. Details different components, describing technically interfaces, protocols, and respective behaviour. From requirement point of view, ensures the mapping of key system characteristics as well as the traceability of the activities identified in usage viewpoint to functional viewpoint to its realization in the implementation viewpoint.

PF share similar challenges and requirements as manufacturing digitisation, resulting on a huge opportunity of technological and knowledge transfer from *Industrie 4.0´*s design principles, standards, and technologies[21][15]. Nevertheless, PF´s by producing living organisms require to consider specific needs, such as real-time plant health monitoring, dynamical optimal control of growing environment, etc, not necessarily considered by manufacturing.

# Chapter 3 Plant Factory IoT Reference Architecture

This chapter intends to make the transition from the Industry's Internet of Things concepts and reference architecture formalised by RAMI4.0 and IIRA as described in 2.4 Digital platforms for Industry, by consolidating both, adapted to support PF.

## 3.1 System Architecture

For the current purpose, it is considered relevant to map the Architecture Layers and Functional aspects from RAMI 4.0 and IIRA respectively into a three-tier system architecture (Figure 13). The three-tier architecture provides improved organization and separation of the different macro components to be implemented. The Edge tier is on the shopfloor, deployed in its own proximity network, comprehending the Asset, Integration, and Communication layers, and possibly some aspects of the Information layer described in RAMI. From IIRA's representation viewpoint, the Edge tier includes the Control Domain and possibly some aspects of the Operations and Information Domains.

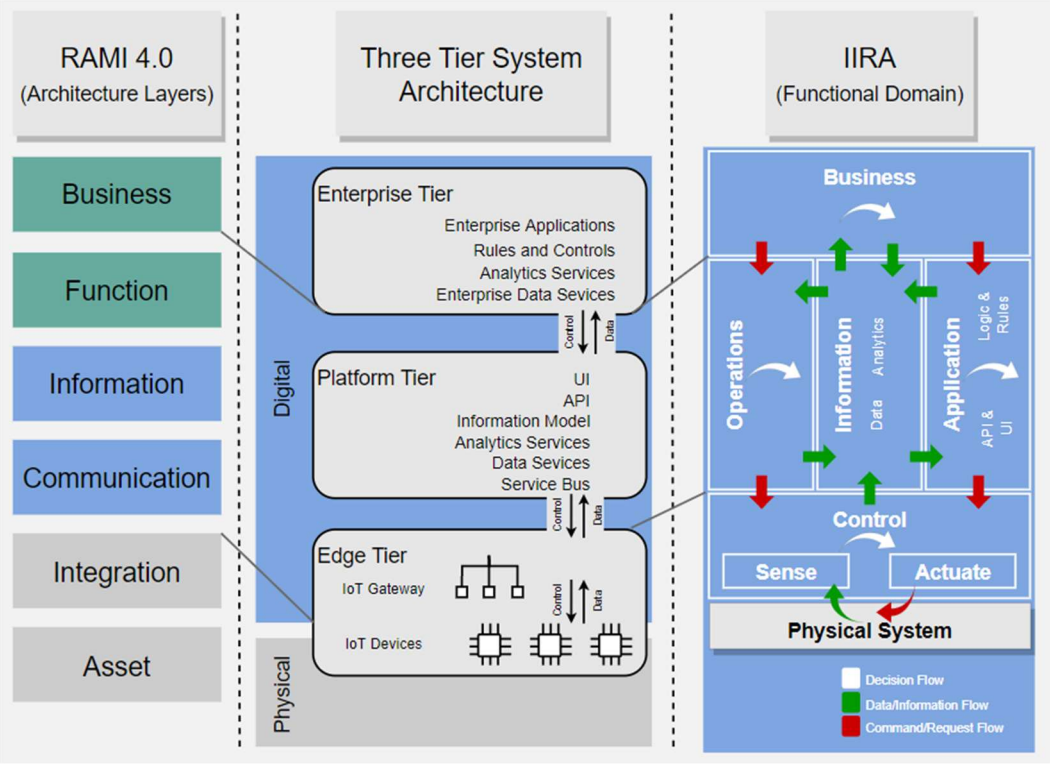



*Figure 13 RAMI 4.0 and IIRA mapping into three-tier architecture.*

The proposed logical system architecture for plant factories (Figure 14) is organized in three level:

### 3.1.1 The Platform tier

This receives data from Edge tier, to be processed and contextualized with data from the Enterprise tier or other external sources. This tier is the brain of IIoT architecture, where data is processed, curated, and explored, model the physical phenomena resulting on information and knowledge generation that then is subsequently is applied as best actions on the physical environment subject to the predefined objectives. These actions are submitted to the edge tier in the form of command controls. To fulfil this workflow, Platform tier comprehends two domains:

- **Operations Domain**, containing a set of functions to support the operationality of PFIoT, both from Platform Management, i.e. hardware, software and user; and Operations Management, i.e. functions related to information management and logic execution orchestration.
  - **Platform Management**, responsible for provisioning, management and monitoring all elements in the platform, for instance devices, applications, and users, and covering their entire lifecycle such as onboarding and configuration, monitoring and retirement. Among the functions required are identity and access management, both applied to both user and applications; device management responsible for the entire assets lifecycle in the platform, from asset registration, configuration, firmware updates to retirement; asset metadata both technical and operational, describing the properties (static or slow changing) and operational performance (dynamic) of assets, and finally monitoring, logging and notification of all platform relevant activities form the platform technical perspective, i.e. continuous verification that all architectural components are secured and performing as per specification, producing notifications when deviation from desired state is detected.

  - **Operations Management**, is the core engine for planning, executing, and monitoring daily cultivation activities. It acts as the link between high-level business objectives defined in the

Enterprise Tier and the physical actions performed at the Edge Tier. This is achieved through the following functions:

- Business Process Integration: It connects with enterprise systems (like ERP) to receive production goals.
- Recipe Management & MPM Repository: It provides the tools to create, manage, and store detailed cultivation recipes, the step-by-step instructions for the entire growth cycle.
- Recipe Schedule and Control: It translates these recipes into timed, actionable tasks and dispatches them to the specific controllers and actuators on the Edge Tier, ensuring that production goals are executed precisely across all units.

### 3.1.2 The Enterprise tier

This tier fulfils different business domain applications and decision support systems, that as whole reflect business objectives, constraints, and products, which in turn are embodied in production requirement requests sent to the Platform tier. In turn, the Platform tier reports back to the Enterprise tier operational information, such as execution progress, asset performance, etc, useful for enterprise functions such supply chain management, asset performance management, inventory management, etc and overall business analytics and optimization. Additionally, the Enterprise tier could be the place to facilitate R&D and collaboration within the industry ecosystem, providing the infrastructure to support these initiatives.

### 3.1.3 The Edge tier

This tier represents the different edge nodes attached to assets or locations of interest, capacitated to control the physical environment through sense and actuate loop. This tier is heartbeat of the IIoT architecture, where data describing the state of physical environment is continuously collected, and subsequently receive control commands to actuate on it. As result, edge tier must comprehend integration and communication capabilities (OT and IIoT Connectivity). Each edge nodes must contain an application, i.e., embedded firmware responsible for retrieving sensor readings, submit control commands, device to cloud connectivity and device security. Additionally, computing and storage capabilities are typical requirements to enable edge intelligence in line with IIoT design principles such as Real Time Capabilities and Decentralization (Figure 9). Depending on existing requirements and/or constraints Edge nodes could be implemented in different coexisting topologies, such as Application-Sensor, Application-Controller-Actuator, Application-Sensor-Application-Controller-Actuator.

To ensure interoperability and extensibility of edge tier deployment, edge nodes need to be decoupled not only among themselves but also from the Platform tier. For that reason, all edge nodes interactions are intermediated through the Edge gateway, which itself should contain capabilities to support edge intelligence, allowing some functions typically residing in Platform tier, to be delegated or temporary pushed down to the Edge tier, and eventually to edge nodes. This system characteristic is of particular importance

to overcome technological or infrastructure constraints, such as latency, network traffic, cost, etc.

Edge tier is comprised by:

- **Operational technology** (OT) Connectivity comprehends the Industrial Ethernet protocols such as Profinet or EtherCAT; standard frameworks for data exchange such as OPC UA; standards used for connecting sensors and actuators to industrial fieldbus or industrial ethernet such as IO-Link, and low-level hardware communication protocol between microcontroller (MCU) and devices (e.g., sensors). This architecture macro component is the closest to the physical environment responsible to retrieve readings from and send commands to it.
- **Edge computing** comprehends a collection of resources primary to aggregate and route data from OT to IT space and inversely submit actions in the form of commands from IT to OT. The level of sophistication of this architectural macro component can vary, combining different resources to increase overall architecture robustness, resilience, efficiency, and effectiveness. Edge tier is the interface between physical and digital making it a critical runtime element in the overall architecture, thus moving computational capabilities such as data visualisation, data transformation, storage, operational logic, etc to the edge nodes, would allow CPSs less dependent from the Platform tier and therefore less susceptible to latency issues (i.e., faster reaction) and access disruption. Additionally, computational capabilities would allow strategies to handle vast amounts of data to be transferred to Platform tier, applying techniques such as data aggregation, data compression[125][126], batch transfers, etc. Additional services must be considered, such as security protocols and mechanisms to administer the edge nodes deployed in the network.

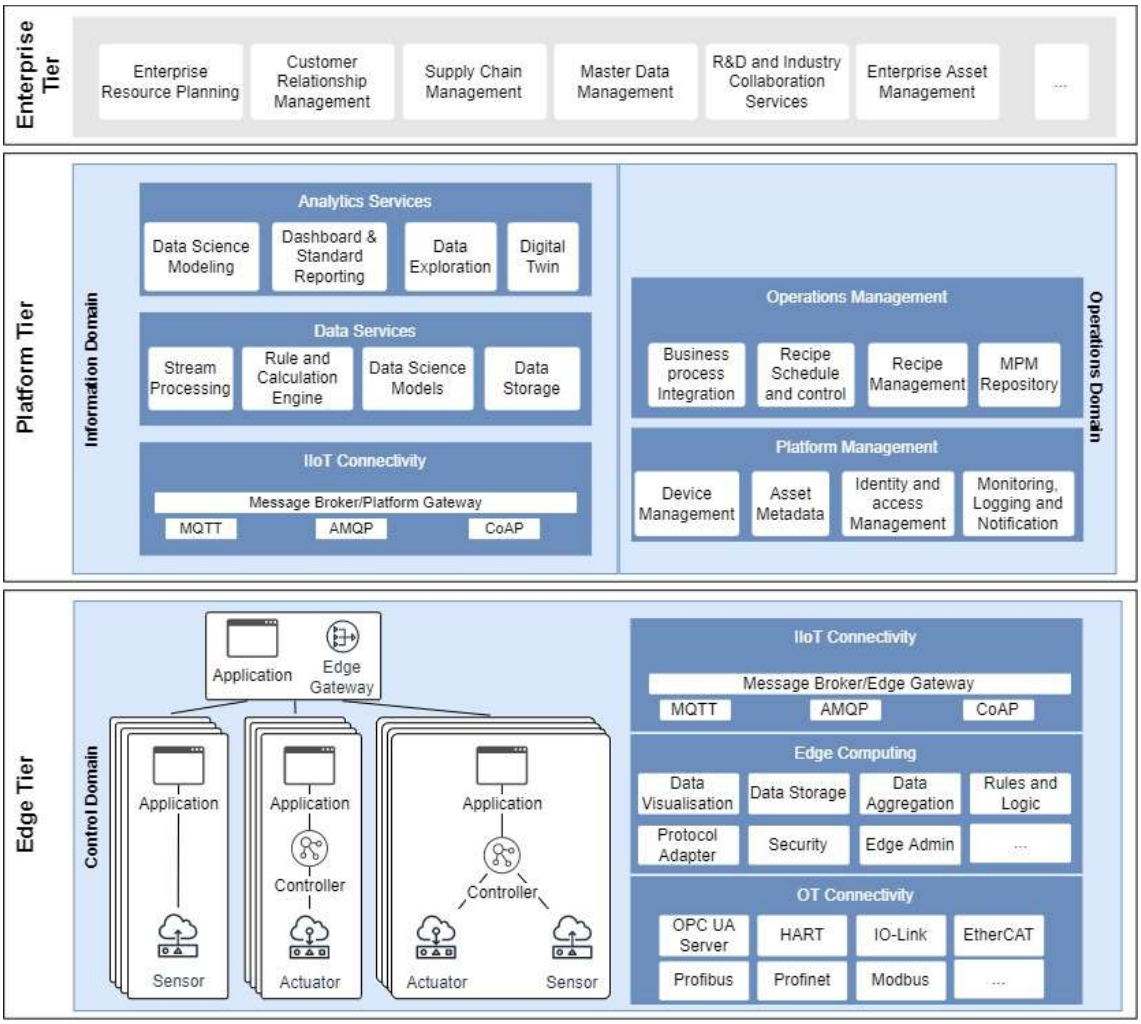



*Figure 14 PFIoT logical system architecture*

## 3.2 Technical enablers for Plant Factories

Realizing the potential of PFs and in line with Industrie 4.0, relies heavily on integrating various technologies for monitoring, control, automation, and data management. This section reviews key technological components and concepts.

### 3.2.1 Plant Production

Figure 15 Plant production system (source [5]) provides a representation of a plant production system, where production inputs on the left are introduced to growing environment, such as the genetic material (seeds or plant transplants), labour and all components required for biochemical process (i.e. photosynthesis). The process yields the intended produce (plants), releases byproducts like oxygen (O2) and water vapor (H2O), and results in energy exchange that affects the ambient temperature. The distinctive nature of IoT systems for PF (PFIoT) are both the type of variables being controlled and required capability to define desired setpoints (SP) which have cross effects on corresponding measured process variable (PV) and output objective(s). In addition, there is a cause-effect of these dynamics on the PVs through the biochemical reactions. In essence PFIoT system could be seen as a homeostasis system, i.e., self-regulating process which in turn is synchronised with the phytobiological homeostasis, guiding the intended plant responses, by optimal adjustment of environment conditions.

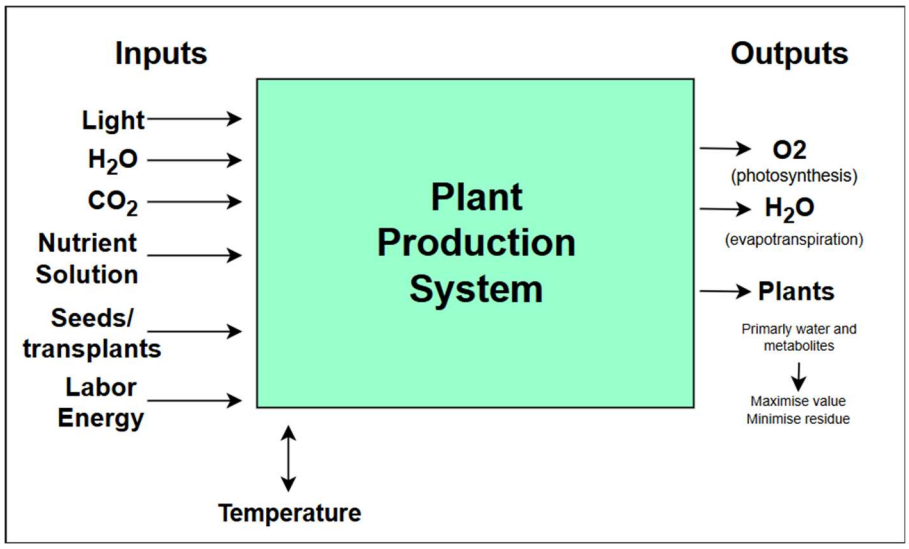



*Figure 15 Plant production system (source* [5]*)*

As result at PF's Control Domain (see 2.4.2.2) must include specific sense and control capabilities allowing to implement the following subsystems [92]:

**Nutrient supply subsystem**, a semi-closed system produces the nutrient solution, with the right chemical proportion, electric conductivity (EC), and potential hydrogen (pH). The nutrient solution is subsequently administered to the plants' radicular system, through a nutrient film technique. Nutrients uptake varies depending on the crop variety and environment conditions. The subsystem recirculates the nutrient solution, monitoring any deviations from the intended state and applying corrective actions when needed. Figure 16 depicts the different components:

1) Nutrient Solution level is continuously verified and if below a predefined threshold the controller activates the water's solenoid valve until the required level is satisfied.
2) The fertilizer concentration in the nutrient solution reservoir is evaluated by the proxy variable electric conductivity (EC), when below of intended bound, the actuator activates the metering pumps, adding the precise quantity of fertilizer required. Changes in the nutrient solution are likely to result in pH changes, requiring the addition acid or alkaline solution to stabilise it around the intended. Temperature significantly impacts pH[127] and EC[128] measurement, being its measurement required compensate measurements.
3) The nutrient solution is conducted from the nutrient solution reservoir to the plants' radicular system through a fluid pump, pressuring the fluid through micro sprayers (aeroponics) or just pumping to the cultivation bed recipient (hydroponics). The irrigation should contemplate an irrigation scheduler, which can activate the irrigation based on defined rules.
4) The water supplied to the cultivation beds is recirculated back to the nutrient solution reservoir together with the water captured by the dehumidifier.
5) To achieve a great level of automation, it should be able to purge the nutrient solution, supporting maintenance activities such as replacement of nutrient solution due to biochemical contamination.

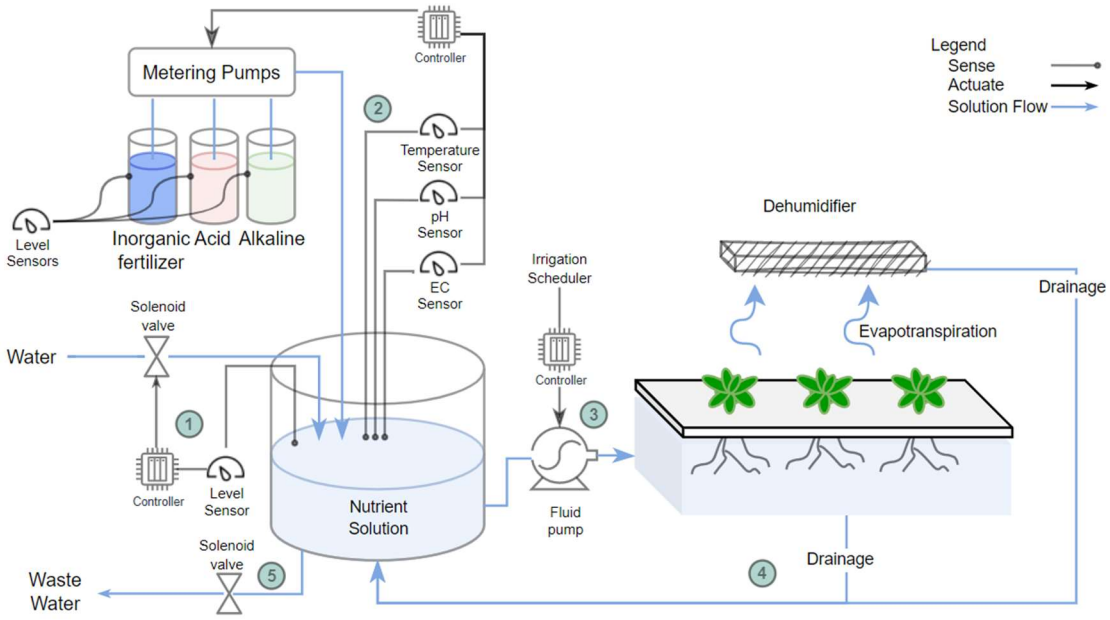



*Figure 16 Nutrient Solution Supply Subsystem*

**Air control subsystem** (Figure 17) ensures optimal conditions of temperature, humidity, $CO_2$, and ventilation of the aerial part of the plant, both to provide the right growth and phytosanitary conditions. The supporting infrastructure comprehends humidity and temperature sensors, and when detected deviations an air heater/cooler and dehumidifier is actuated to stabilise the parameters around the setpoints. Mainly to ensure good phytosanitary conditions (e.g., avoid leaf water condensation) a ventilation system is continuously being operated, providing adjustable airflow intensities. Being one of the main direct inputs for photosynthesis, $CO_2$ is continuously monitored and administered to the environment keeping a stable concentration around the desired setpoint. Root temperature is also another interesting parameter to be monitored and controlled, because its role on nutrients uptake, growth, physiology, and accumulation of bioactive compounds [56],[49],[51],[55].

Optimal environment conditions could be found by measuring photosynthetic rate associated with all controllable variables. Photosynthetic photon flux density (PPFD) is approximately limited between 100 and 300µmol $m^{-2}$ $s^{-1}$ in a plant factory, therefore the main controllable factor in this subsystem, affecting photosynthesis is temperature[40]. The photosynthetic rate can be inferred if the environment is hermetically set, by measuring $CO_2$ consumption rate as result of photosynthesis.

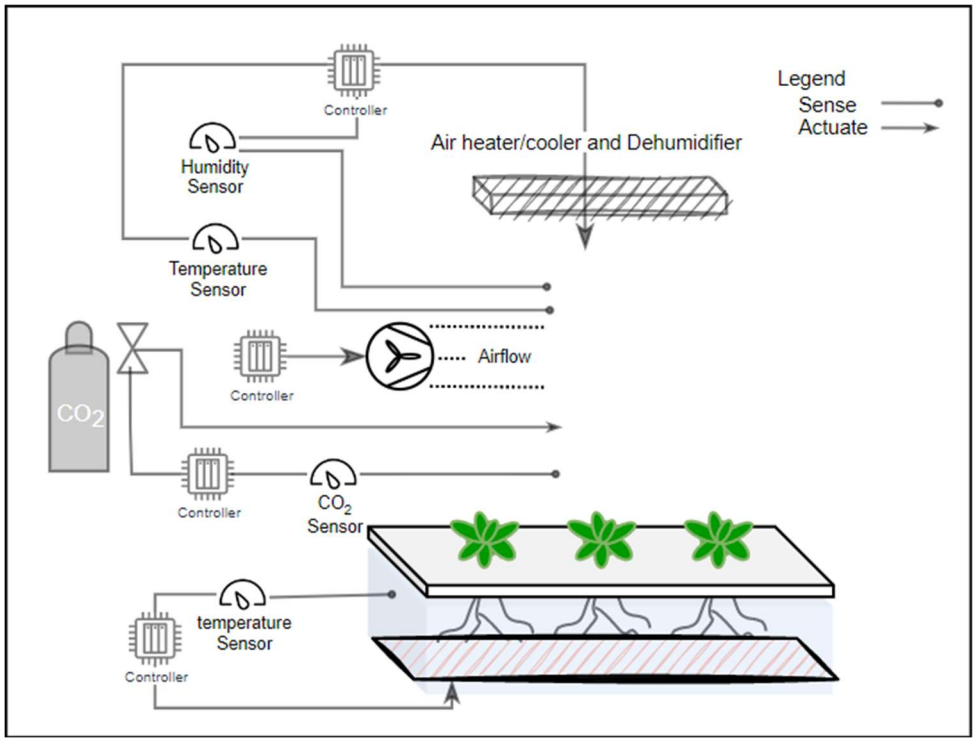



*Figure 17 Air control and root temperature control subsystem*

**Light subsystem** ensures optimal supply of photosynthetic active radiation (PAR) to the plants, i.e. the portion of the light spectrum utilised (400-700 nm) by plants for photosynthesis. Since plants lifecycle is highly dependent and phenotypically responsive to both the photon wavelength and photoperiod[38], [42], [43], the system must be able to control both light spectrum and light/no light duration cycles. The lag between photon lux applied to plants and resulting phenotypic responses, as well the ability to monitor it in a continuous and non-destructive manner, makes impractical to implement feedback loop control in this subsystem. As result it is assumed the implementation of a schedule plan of periods of light and darkness, and light spectrum, in accordance with plant's lifecycle needs and phenotypic objectives.

Despite of predefined, stateless rules defining the light schedule, it is required to monitor actual PAR supplied to the plants to verify the correct light positioning, alignment between setpoints and actual values, and not least important generate historical data allow to model the effect of production environment on different intended phenotypic features, being light one of the main factors. For this purpose, Photosynthetic photon flux density (PPFD), should be used as a measure in micromoles that expresses how many PAR photons are landing per square metre per second (µMol/m2/S)[129].

These instruments are often called full-spectrum quantum sensors, operating typically within the spectral range 400 to 700 nm ± 5 nm [130], [131], [132], [133].

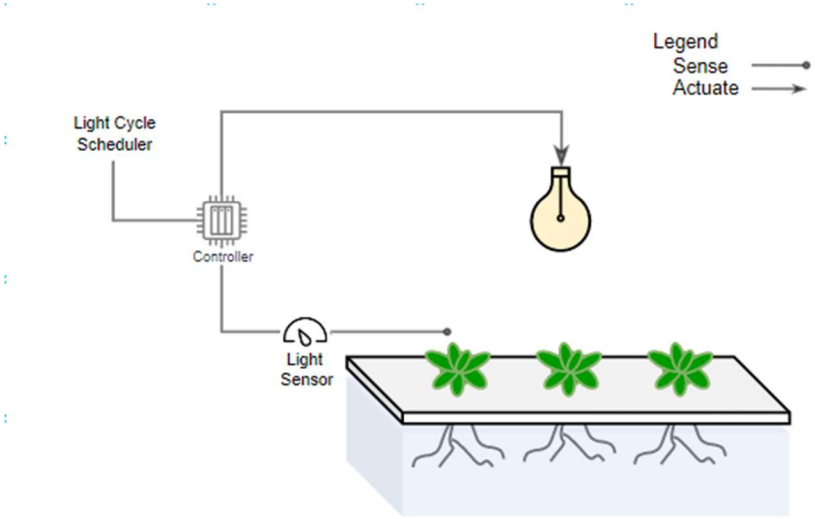



*Figure 18 Light control sub-system.*

### 3.2.2 Mushroom production

Mushroom cultivation involves managing the lifecycle of fungi, which in the context of this study, differs significantly from plant production. A simplified mushroom production system involves introducing inputs to a controlled growing environment to raise fungal growth (mycelium) and subsequent fruiting (mushrooms).

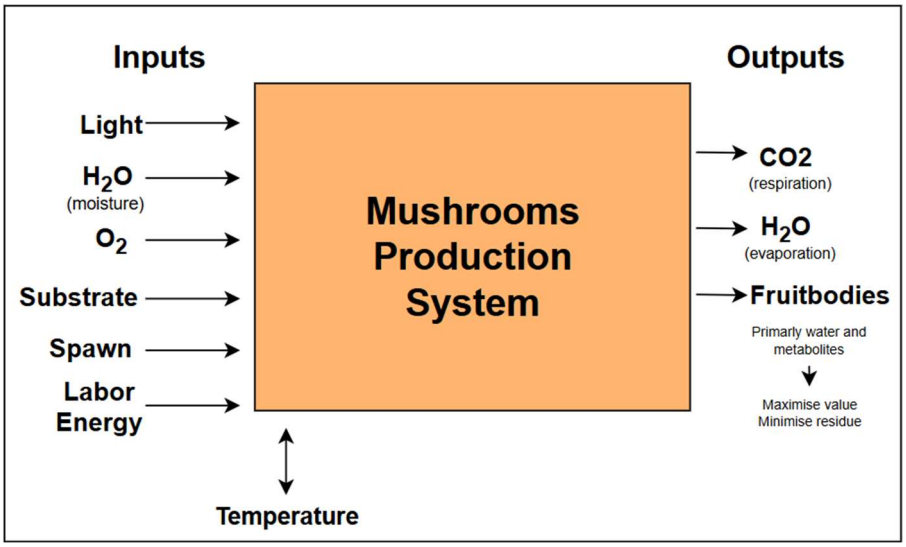



*Figure 19 Mushroom production system.*

Figure 19 provides a representation of a mushroom production system, where production inputs on the left are introduced to growing environment. The necessary inputs for this process include mushroom spawn (the carrier inoculated with mycelium), a suitable substrate (the nutrient medium, such as compost, straw, or sawdust), water (for substrate moisture and humidity), energy (for environmental controls like heating and cooling), and labour (for preparation, inoculation, and harvesting). The desired outputs are primarily the mushrooms themselves, along with byproducts such as carbon dioxide ($CO_2$), water vapor ($H_2O$), heat generated from metabolic processes, and the remaining spent substrate after harvest.

The core challenge lies in precisely controlling environmental variables (temperature, humidity, $CO_2$, $O_2$, air exchange) throughout the distinct phases of mushroom development: substrate preparation/sterilization, inoculation, spawn run (mycelial colonization), pinning (initiation of fruiting bodies), and fruiting (mushroom maturation). Unlike plants, mushrooms do not photosynthesize; they are heterotrophs, deriving energy from the substrate and respiring oxygen while releasing $CO_2$.

#### *3.2.2.1 Key Subsystems for Controlled Mushroom Production.*

**Substrate preparation:** involves mixing ingredients according to specific formulations tailored for the intended mushroom species and its subsequent mycelial inoculation. A critical step in substrate preparation is pasteurization or sterilization (using steam, heat, or chemicals) to eliminate contaminating microorganisms that could lead to total production loss. This subsystem is not detailed in the current study, as its focus is on controlling the production environment.

**Air control subsystem (**Figure 20) ensures optimal conditions of temperature, humidity, CO2 levels, and ventilation within the mushroom growing environment, crucial for both promoting robust growth and maintaining hygienic conditions necessary for mushroom healthy development. The supporting infrastructure includes sensors for humidity, temperature, and CO2. When deviations from desired setpoints are detected, control systems actuate equipment such as air heaters/coolers, humidifiers/dehumidifiers, and the controllable ventilation system (managing fans/dampers for Fresh Air Exchange - FAE) to stabilise parameters.

$CO_2$, a significant byproduct of mycelial respiration, requires careful management throughout the cultivation cycle [75], [76]. This management is complex because both

the rate of $CO_2$ emission and the mycelium's tolerance to it change dramatically depending on the developmental phase. During the spawn run phase, where the mycelium colonizes the substrate, high CO2 concentrations (e.g., 5,000-20,000 ppm) are often maintained as they can be beneficial for vegetative growth (see Table 2). However, to trigger pinning (the initial formation of mushrooms) and support healthy fruiting body development, CO2 levels must be drastically reduced [75], typically to below 1,000-1,500 ppm for many cultivated species (see Table 2 for species-specific examples). This critical reduction is achieved by introducing controlled Fresh Air Exchange (FAE) via the ventilation system, which requires precise control over air exchange rates.

The ventilation system, incorporating components like fans (often variable speed), dampers, and potentially air filters, is therefore vital. It manages CO2 reduction via FAE, inherently influencing and maintaining necessary oxygen levels as well. Furthermore, it must provide gentle, consistent air movement. This controlled airflow is essential to distribute temperature and humidity evenly throughout the growing space, remove metabolic gases accumulating in the mushroom microclimate, and maintain good hygienic conditions (e.g., preventing excessive surface moisture and stagnant air), all while being careful not to dry out the developing mushroom caps.

Mushrooms generally require high relative humidity, often 85-95%+, especially during pinning and fruiting [75] (see Table 2), to prevent drying out. This involves humidifiers (e.g., foggers, moister), dehumidifiers (if necessary, though often managed via ventilation), and RH sensors (Figure 20).

Monitoring and controlling substrate temperature is critical because it significantly impacts the overall environment temperature and plays a vital role in the rate of mycelial colonization, nutrient uptake from the substrate, overall fungal physiology, and potentially the accumulation of bioactive compounds.

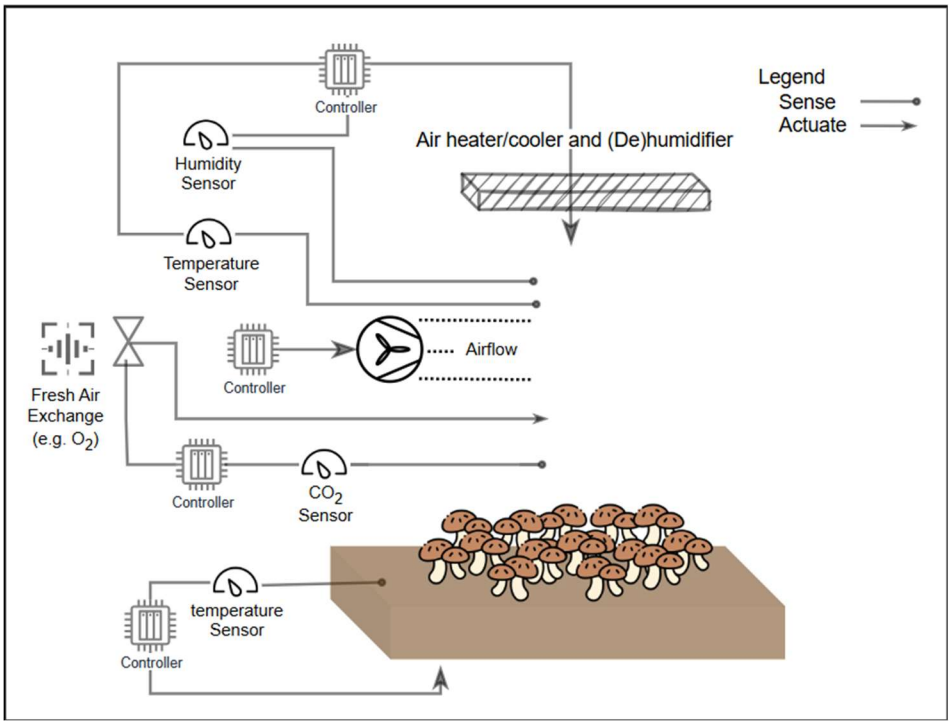



*Figure 20 Air control for mushrooms.*

**Lighting Subsystem:** Unlike plants, mushrooms do not use light for photosynthesis. However, for many species, light is a crucial environmental signal that initiates fruiting (pinning) and guides development, affecting characteristics such as cap colour, stem length, and even nutritional value [134]. While low-intensity light, particularly in the blue spectrum, has traditionally been used [134], [135], [136]. the optimal light spectrum for each mushroom variety is not yet clear and remains an area of active research. For this reason, full-spectrum LED lights are the preferred choice. This technology not only allows for continuous improvement and experimentation with different light "recipes" but also not only are energy-efficient but also produce minimal heat, preventing an undesirable impact on the grow room's temperature. The control system must manage specific light/dark cycles during the fruiting stages, similar to the lighting subsystems used in plant production Figure 21.

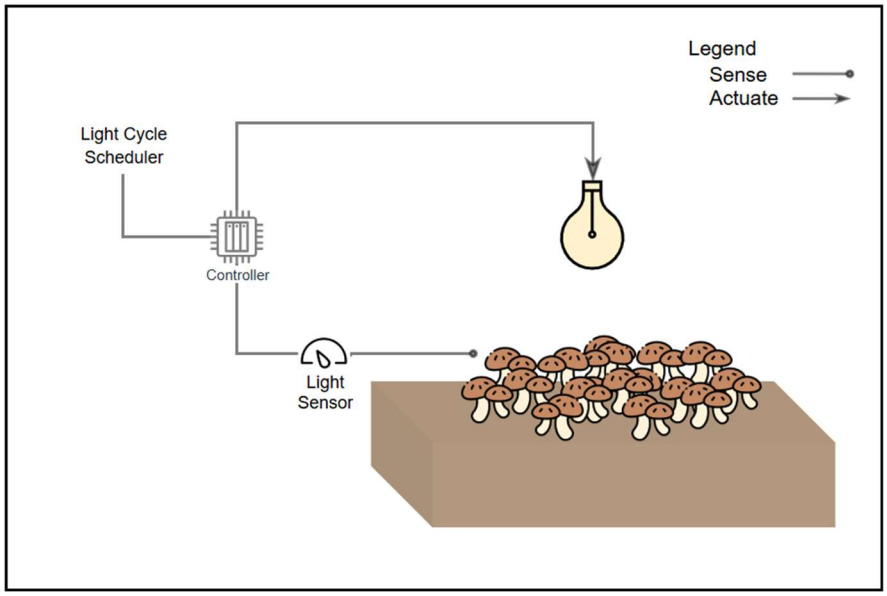



*Figure 21 Light subsystem for mushrooms*

### 3.2.3 Fungi and Plant Symbiotic relation in Closed-Loop Plant Factory Model

Plant factories that combine both mushroom and plant production present an opportunity for circular, closed-loop integration within advanced controlled environment agriculture systems, targeting resource utilization optimisation, economic viability, and sustainability goals. The symbiotic integration of mushrooms and cultivated plants can create a more comprehensive circular system. While, as described in section 2.2.3, the complementary exchange of $CO_2$ for plant photosynthesis and $O_2$ for mushroom respiration is a key benefit, the synergy extends to other areas. This integrated approach presents opportunities for nutrient cycling through waste valorisation (using plant residues as substrate and spent mushroom substrate as fertilizer), as well as potential synergies in water and heat management.

The integrated system comprises two types, interconnected production units designed to achieve enhanced resource circularity: the Plant Production Chamber and the Fungal Cultivation Chamber.

**Plant Production Chamber:**

This unit houses cultivated plant species, typically grown using hydroponic or aeroponic methods. Environmental parameters, including photosynthetically active

radiation (PAR) provided by optimized LED lighting, temperature, and humidity, are precisely controlled to maximize photosynthetic rates and plant growth. The primary contribution of this chamber to the integrated system's circularity is the generation of oxygen ($O_2$) as a direct byproduct of plant photosynthesis. This $O_2$-rich air is a critical output stream utilized by the fungal cultivation unit.

**Fungal Cultivation Chamber:**

Dedicated to the production of edible fungi, such as Pleurotus ostreatus, this chamber unit provides a controlled environment for fungal development on specialized organic substrates. These substrates are predominantly composed of lignocellulosic materials, supplemented with essential nutrients. Through metabolic respiration and substrate decomposition, the cultivated fungi release carbon dioxide ($CO_2$). This $CO_2$-rich air constitutes a key resource stream directed towards the plant production unit. Furthermore, this chamber facilitates the biotransformation of complex organic waste materials from the substrate into fungal biomass and partially decomposed Spent Mushroom Substrate (SMS)[137], [138].

**Integrated Exchanges and Circularity:**

The operational principle of this system hinges on the deliberate integration and exchange of resources between the two chambers, establishing multiple circular loops:

- **Atmospheric Gas Exchange:** The central mechanism involves the reciprocal flow of respiratory gases. $O_2$-enriched air exhausted from the Plant Production Chamber is supplied to the Fungal Cultivation Chamber to support aerobic fungal respiration[139]. Concurrently, $CO_2$-enriched air emanating from the Fungal Cultivation Chamber is directed into the Plant Production Chamber to augment ambient $CO_2$ concentrations, thereby enhancing plant photosynthetic efficiency. This exchange significantly reduces reliance on external gas inputs.
- **Nutrient and Material Cycling:** Material circularity can be achieved through the valorisation of organic streams. Plant biomass residues can be repurposed as components within the fungal growth substrate. Subsequently, the SMS represents a valuable source of nutrients, made more bioavailable through fungal decomposition. Processed SMS can be recycled and incorporated back into the plant production system as a fertilizer or substrate amendment [137], [138], [140],

closing a critical nutrient loop. Additionally, SMS can be used through pyrolysis and gasification to produce energy for use by the plant factory [137], [141].

- **Water and Energy Synergy:** Further resource efficiencies are attainable through the management of water vapor and metabolic heat. Water transpired by plants and evaporated from mushroom substrate contributes to the chamber humidity, which can be condensed and recycled within the system's water loop[142], [143]. Additionally, metabolic heat generated during fungal growth offers potential for thermal integration, contributing to the overall energy balance of the facility.

These integrated exchanges across gaseous, material, and energetic domains define the closed-loop nature of the combined mushroom-plant cultivation system, contributing significantly to resource optimization and the sustainability goals of advanced controlled environment agriculture.

# Chapter 4 Plant Factory prototype.

This chapter details the design and implementation of a prototype system for controlled environment agriculture (CEA). A key focus of this prototype is to demonstrate support for the monitoring and control of multiple production units or facilities, serving as a practical realization of the theoretical architecture.

The prototype's architectural structure is based on the proposed Plant Factory IoT architecture described in Chapter 3 (“Plant Factory IoT Reference Architecture”) and illustrated in Figure 14 (“PFIoT logical system architecture”). This multi-tiered architecture, comprising Edge, Platform, and Enterprise layers, is fundamental to achieving the extensibility, scalability, modularity, and interoperability essential for complex IIoT deployments[144], [145], [146]. It effectively isolates real-time operational functions at the edge from data processing and eventual enterprise integration functions.

The primary objective of this prototype is to validate the practical applicability and efficacy of the reference architecture. Specifically, it aims to demonstrate the integration of grow recipes, sensors, and actuators within a feedback control loop setting. This includes showcasing data ingestion from environmental sensors, execution of control logic based on predefined growth recipes, persistent storage of time-series data, and visualization for operational oversight and future analysis. This prototype aims to be the starting point for future special focus on a generic and reusable data model and standardized agent that incorporates feedback loop control and a standardized way to convert controls into actuator actions at the edge.

Furthermore, this chapter details the development and evaluation of a small-scale plant factory prototype designed to demonstrate the feasibility and benefits of integrating plant and fungal cultivation within a closed-loop system. The prototype aims to establish a standardized PFIoT architecture capable of supporting the concurrent production of both plants and mushrooms. This architecture will facilitate precise environmental control and optimize resource utilization by harnessing the complementary gas exchange requirements of these two disparate organisms, specifically the re-utilization of byproducts such as $CO_2$ and $O_2$, which are critical for plant photosynthesis and fungal respiration, respectively.

To ensure feasibility and streamline the initial development process, the prototype has been constructed at a reduced scale. For practical reasons and time feasibility, certain aspects were descoped from the prototype:

- Monitoring and control of the Nutrient Supply Subsystem: Water and nutrient control is manual for the hydroponic setup.
- Light subsystem: Control is restricted to the photoperiod, meaning grow lights are used but only their duration is controlled, still the prototype supports diverse light types, only ultraviolet (UV) and red spectrum lights were used.
- Edge compute: prototype did not evaluate the benefits of moving compute to the edge for improved system resilience against network failing points or for reducing control loop latency across multiple locations. However, the underlying technical architecture, implemented using containerization, provides the necessary foundation and flexibility to port system components to the edge.

This prototype demonstrates the feasibility of a PFIoT platform that supports integrated plant and fungal cultivation within a closed-loop system. The prototype's system architecture encompasses a subset of the PFIoT logical system (Figure 14).

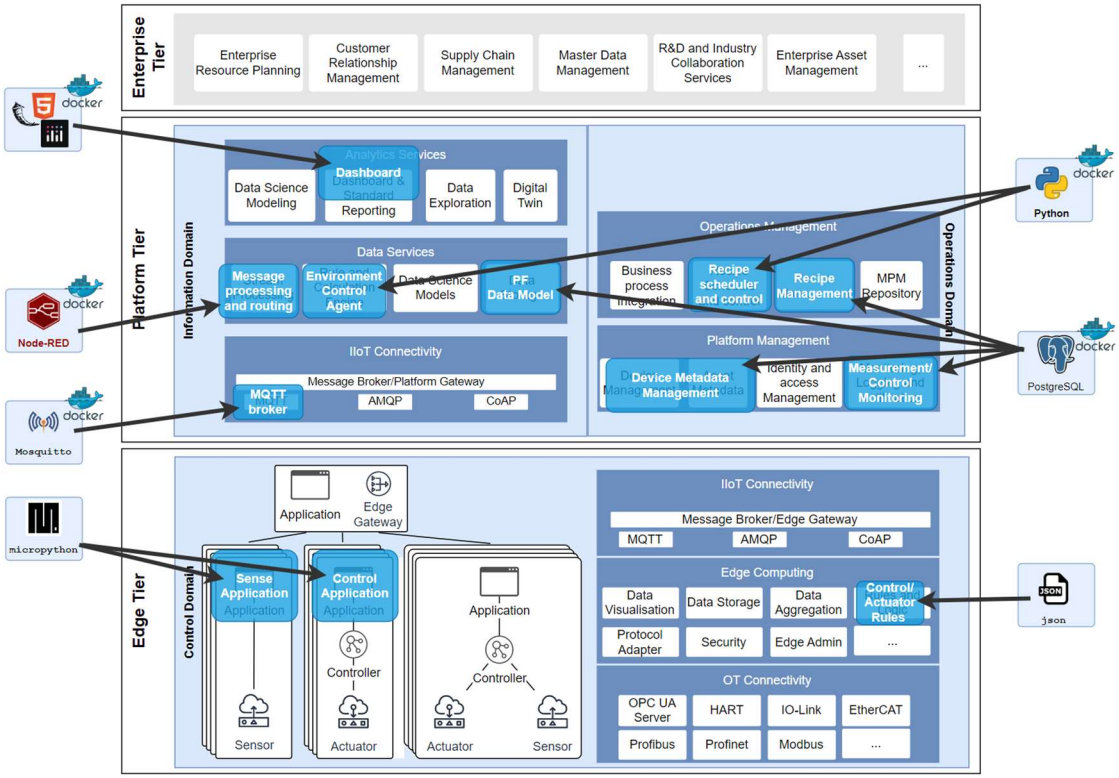



*Figure 22 Architectural Scope of the PFIoT Prototype*

The realization of this prototype leverages a set of technologies, selected for their suitability within the IIoT and grow operations context.

## 4.1 Platform Tier Implementation

The Platform Tier serves as the central nervous system of the IIoT solution, orchestrating data flow, providing essential services, and bridging the edge and enterprise systems. Specifically, this intermediate tier aggregates data from multiple edge devices and offers core services such as data storage, processing, device management, and relaying environment control commands to the edge. A key technology selection principle for this layer was the prioritization of Free and Open-Source Software (FOSS), driven by the goal of establishing an open and accessible platform specifically suited for Controlled Environment Agriculture (CEA) community. Consequently, the technologies chosen included:

- Eclipse Mosquitto for message brokering [147]
- Node-RED for message processing and routing [147]
- PostgreSQL for database management [148]
- Python for application logic implementation [149]
- Docker for containerized deployments[150].

Key characteristics of this design include:

- **Hierarchical Location Management:** The schema allows for defining physical locations (facilities) and subdividing them into production units. A "unit" represents a distinct, manageable production area (e.g., a specific greenhouse, a vertical farm floor, or an isolated container) within a facility, where the production volume (calculated from area and height) is a key factor for environmental control. These units can be further divided into specific zones, which is particularly useful for controlling environmental conditions within large production volumes (area x height).
- **Device and Component Tracking:** It provides a detailed inventory of IoT devices (sensors, actuators) deployed within the CEA environment, including their types, specifications, locations (zones), and individual components.

- **Recipe Definition and Execution:** The platform supports the creation of environmental control recipes, detailing specific parameters (temperature, light, CO2, humidity) for different stages or cycles. It also tracks the execution instances of these recipes within specific production units.
- **Data Logging:** A mechanism exists for logging measurements received from devices, capturing the environmental data essential for monitoring and control. Additionally, it supports logging all control commands submitted to the unit/zone as well as the resulting actuation applied at the edge device level. This comprehensive feedback control loop traceability, i.e. sensor data points, control commands, setpoints, and feedback sensor data, is the foundational data that allows the platform to move towards reinforced learning strategies to optimize environment control.
- **Scalability:** The design can accommodate multiple production units, potentially distributed across various locations, making it suitable for multi-facilities and multi-tenant growing operations.

### 4.1.1 The information domain

The Information Domain is a cornerstone of the Platform Tier within the PFIoT architecture (see Figure 14). It is primarily responsible for the comprehensive management of all data flowing to and from the Edge Tier, as well as data generated within the Platform Tier itself. This domain encompasses the crucial functions of data ingestion, secure and reliable communication (IIoT Connectivity), data processing and transformation (Data Services), persistent storage, and making data accessible for higher-level applications such as analytics, reporting, and operational control. Its role is to convert raw data into structured, contextualized information that can be leveraged by other domains and services to drive insights and intelligent decision-making for the CEA system.

#### *4.1.1.1 IIoT Connectivity*

IIoT Connectivity forms the foundational communication layer within the Information Domain, responsible for establishing and managing the data exchange pathways between the Edge Tier devices, the Platform Tier services, and potentially external systems. This component ensures that sensor data, actuator commands, and other operational messages are transmitted securely, reliably, and efficiently. It typically involves the implementation of standardized communication protocols and message brokers that can handle the scale and real-time requirements of an Industrial Internet of Things environment. For the PFIoT prototype, this involves mechanisms like MQTT for message queuing and telemetry transport, enabling decoupled communication between various system components. Effective IIoT connectivity is paramount for timely data acquisition, responsive control, and overall system integration.

##### 4.1.1.1.1 MQTT Broker

Eclipse Mosquitto serves as the Message Broker/Platform Gateway component within the architecture. This component functions as the IoT connectivity layer, enabling secure and reliable data exchange between Edge Tier devices and Platform Tier services. It is implemented using the Mosquitto MQTT broker, a lightweight and efficient messaging broker widely adopted in IoT applications. This component is designed to architecturally support loose coupling, a design pattern where edge and platform system components minimize their dependencies on each other, enhancing flexibility and maintainability. Data exchange is facilitated via this MQTT broker, where applications communicate

using a publish/subscribe approach. A standard convention is used for message topics (see example in Figure 23):

**Topic:** <Root>/<Unit Code>/<Zone Code>/<Type of Message>/<Scope>

- **Root:** Used as a prefix to fully separate topics belonging to different platform tenants.
- **Unit Code:** Refers to the specific production unit that the topic relates to.
- **Zone Code:** Refers to a zone within a given production unit. A zone has devices (sensors and controllers) exclusively allocated to it.
- **Type of Message:** Refers to whether the message is a sensor measurement (*sense*), a control command for the edge controller (*control*), or a control setpoint message (*control_setpoint*) which, for traceability, contains the parameters used in actions by the controller.
- **Scope:** Refers to the granular level of the hierarchy, specifying the scope of the message e.g. air_temperature, air_humidity, etc.




*Figure 23 Examples of MQTT messages used in the CEA prototype.*

#### *4.1.1.2 Data Services*

Data Services represent a set of functions within the Information Domain that are responsible for handling the data once it has been received via IIoT Connectivity. These services focus on the processing, transformation, contextualization, and persistent storage of data to ensure its quality, usability, and accessibility for various applications. Key responsibilities include parsing incoming messages, validating data integrity, routing data to appropriate storage or processing pipelines, and structuring data according to the defined Plant Factory Data Model (see Figure 26). For instance, this includes the logic for message processing and routing to capture all feedback loop activities, as well as the mechanisms for storing environmental measurements and control setpoints. The Environment Control Agent, which embodies the core control logic, also relies heavily on the processed data provided by these services to make informed decisions, although its execution orchestration might also be considered part of the Operations Domain. Ultimately, Data Services ensure that raw data is transformed into an asset for monitoring, control, and analytics.

##### 4.1.1.2.1 Message Processing and routing.

There are two types of message processing implemented in the prototype: one related to the feedback control loop mechanism that senses the environment and applies actions (see 4.1.1.2.2 Environment Control Agent), and the other mechanism that strictly ensures all messages are captured and persisted. This subsection focuses on the latter.

The main purpose of this component is to capture all messages, which include sensor measurements, control commands, and actions performed by the actuators. This is a key component that allows for full traceability of feedback loop control activities, essential for monitoring and for 'time-machine' debugging of the system's capabilities. Furthermore, the collected data enables enrichment (e.g., associating data with specific crop batches or recipe stages) and potentially the execution of more complex analytics or predictive models (e.g., yield prediction based on historical data – though this might be a future extension). This data can ultimately be used to optimize actions and recipes with advanced modelling techniques such as machine learning and reinforcement learning (e.g., Q-learning).

This architecture component is containerised in Docker, allowing full portability to a separated infrastructure and keeping it decoupled from the rest of the components to ensure resilience on data to enable operational traceability. In this case, the mechanism is very simple: Node-Red implements a continuous subscription to the root level of the MQTT topic, and JSON payloads containing data are continuously streamed to the database, persisting it in the measurement entity (see Figure 24).

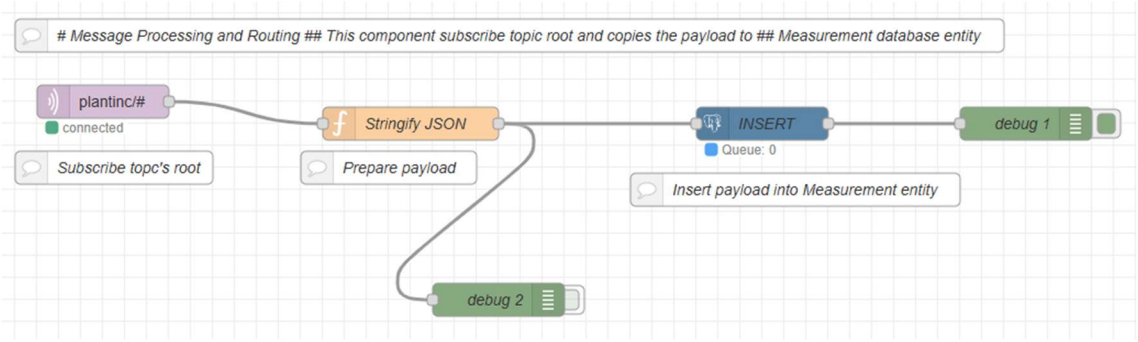



*Figure 24 Message Processing and routing in Node-Red*

#### 4.1.1.2.2 Environment Control Agent

This component implements the core of the feedback control loop using a custom Python function, run_agent() (see Appendix B). At a high level, this function receives parameters (run_params) defining the desired operating conditions for the controlled environment (e.g., temperature range, relative humidity range, day duration, and type of light, etc.). It then executes two distinct functions independently and in parallel using Python threads:

- The mqtt_subscribe_thread() subscribes to topics containing environmental measurements for the relevant production unit.
- The control_logic_thread(), based on the run parameters and environmental measurements, determines actions represented by the following possible commands: UP, DOWN, OFF, ON.

  For example, if the sensed air temperature is less than the defined lower limit (air_temperature < air_temperature_lower_limit), the control command air_temperature UP is issued in the form of an MQTT message.

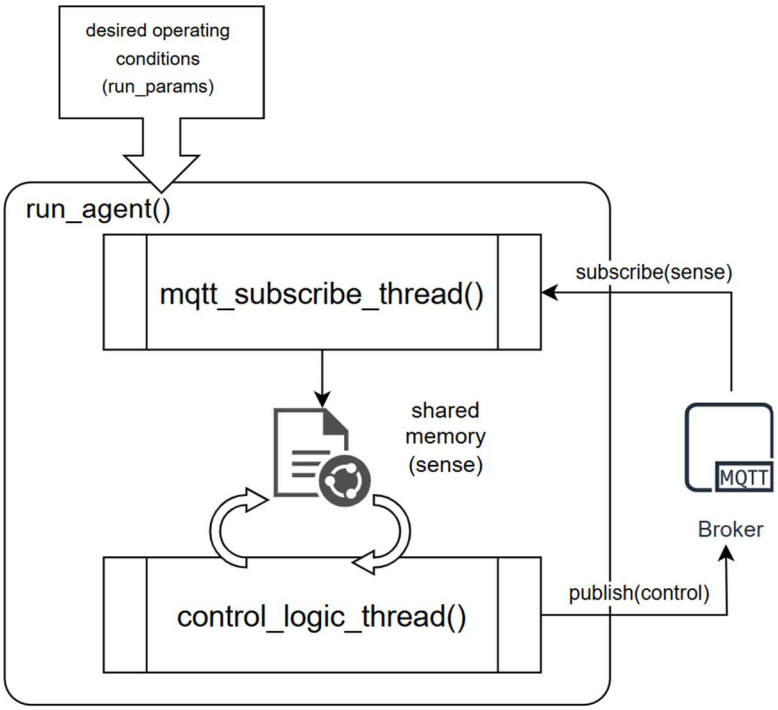



*Figure 25 Environment Control Agent*

The MQTT topic naming convention plays a crucial role in this mechanism. Even though environmental sensing is performed at the unit level, the control logic thread operates at the zone level. The control decision is then published to a topic to which the edge control device of the specific zone subscribes.

The environment control agent is executed by the "Recipe scheduler and Control" (see 4.1.2.1.2 Recipe scheduler and control)

#### 4.1.1.2.3 PF Data Model

Plant factory's data model (Figure 26) establishes the data structure foundation for Controlled Environment Agriculture (CEA) platform. This structure is intended to be generic supporting the management of various aspects critical to CEA operations across potentially multiple physical locations.

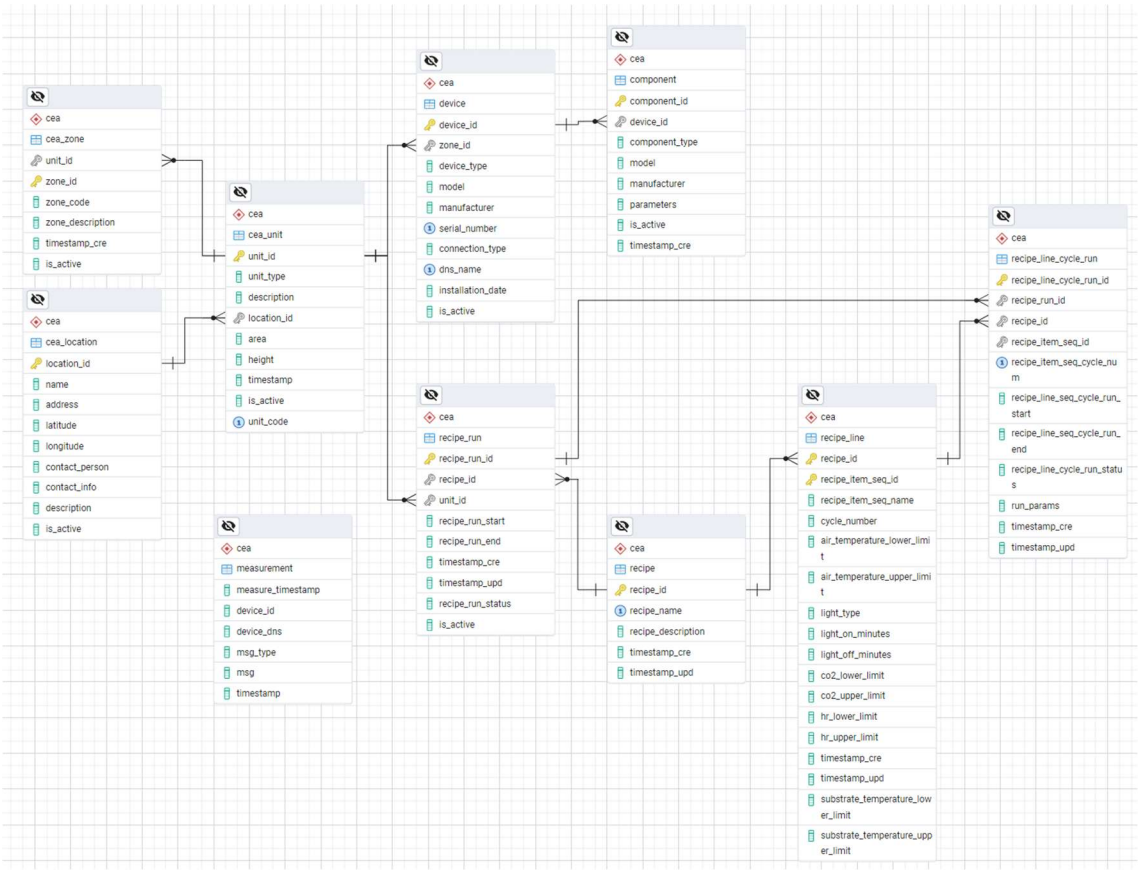



*Figure 26 Plant Factory Database model*

This database model describes the system that manages and monitors the Controlled Environment Agriculture (CEA) setup. It's structured around four main areas: the physical infrastructure, the control recipes, the execution of those recipes, and data measurement.

**Physical Infrastructure & Devices** is the part of the model defines the physical world.

- The entities *cea_location*, *cea_zone*, and *cea_unit* create the hierarchy for the physical space. A location (like a building) contains multiple zones (like rooms), which in turn contain multiple units (like a specific rack or tent).
- The entities *device* and *component* represent the hardware assets deployed in the PF. A device (e.g., a sensor, a light, a pump) is installed in a *cea_unit*. *Devices* can be broken down further into components if needed. This structure allows you to know exactly where every piece of equipment.

**Recipes & Control Logic** is the part of the model that defines the "instructions" for growing something.

- *recipe* entity defines the top-level plan, like "Grow Lettuce".

- *recipe_line* entity specifies how a recipe is made up of multiple lines or production stages, like “vegetative stage” or “flowering stage”. Each *recipe_line* specifies target environmental parameters, such as air temperature limits, CO2 levels, and light-on/off times.
- *recipe_item_seq* entity handles the sequence or specific steps within a recipe line, seen as the number of cycles in a given stage, like flowering stage include 10 day cycles.

**Recipe Execution & Status** is the part of the model that tracks the live operation of a recipe run.

- *recipe_run* is the entity that represents a specific instance of a recipe being executed on a particular *cea_unit*. It tracks the start and end times and the overall status.
- *recipe_line_cycle_run* and *recipe_item_seq_cycle_run* are entities that log the execution of each specific line and item sequence from the recipe. They track when a particular set of conditions (like a lighting cycle) starts, ends, and its status. This provides a detailed historical log of the control system's actions.

**Data Collection** is the part of the model responsible to hold the data logging.

- *Measurement* is a simple but crucial table that logs all data points. It records a value (msg) from a specific device at a specific timestamp. This table captures the raw sensor data, control commands sent bet the Control Logic to the edge and setpoints applied by the edge device. This entity provides the basis for monitoring, analysis, and feedback control modeling.

The follow subsections provide detailed information of each entity.

##### 4.1.1.2.3.1 Location

**Entity Physical Name:** cea.cea_location

Represents a distinct physical facility or farm where CEA operations take place. It stores identifying information such as the facility's name, address, geographical

coordinates (latitude, longitude), contact details, and a general description. The is_active flag indicates if the location is currently operational.

This is a top-level entity. Each unit (Production Unit) must belong to one cea_location, establishing the physical site for each unit via the location_id foreign key in cea_unit.

#### 4.1.1.2.3.2 Production Unit

**Entity Physical Name:** cea.cea_unit

Defines a specific production area or building within a larger cea_location. It captures the unit's type, a descriptive label, its physical dimensions (area, height for volume calculation), a unique code (unit_code) potentially used for backend processes.

**Entity Relation and Rationale:**

- **Belongs To:** cea_location (via location_id). This links the production unit to its physical facility.
- **Contains:** cea_zone (via unit_id in cea_zone). A unit can be subdivided into multiple zones.
- **Hosts:** recipe_run (via unit_id in recipe_run). Recipe executions are specific to a production unit.

#### 4.1.1.2.3.3 Zone

**Entity Physical Name:** cea.cea_zone

Represents a subdivision or specific area within a cea_unit. Zones allow for more granular control and monitoring within a larger production unit.

Entity Relation and Rationale:

- **Belongs To:** cea_unit (via unit_id). This associates the zone with its parent production unit.
- **Contains:** device (via zone_id in device). Devices are installed within specific zones.

#### 4.1.1.2.3.4 Device

**Entity Physical Name:** cea.device

Represents an individual IoT device (e.g., sensor hub, control module) installed within the CEA system. It stores details like device type (Control, Sense, Both), model,

manufacturer, unique serial number, network connection type, network identifier (DNS name or IP), installation date, and operational status (is_active).

Entity Relation and Rationale:

- **Located In:** cea_zone (via zone_id). This pinpoints the specific zone where the device is installed.
- **Composed Of:** component (via device_id in component). A device can consist of multiple functional components (sensors, actuators).
- **Source Of:** measurement (entity) that can be identified device_dns or device_id. Devices generate measurement data.

#### 4.1.1.2.3.5 Component

**Entity Physical Name:** cea.component

Details a specific functional part (sensor or actuator) integrated into an IoT device. This includes the component's type (e.g., 'CO2 sensor', 'heater actuator'), model, manufacturer, specific operational parameters (stored as JSON), and its active status.

Entity Relation and Rationale:

- **Part Of:** device (via device_id). This links the component back to the specific IoT device it belongs to.

#### 4.1.1.2.3.6 Measurement

**Entity Physical Name:** cea.measurement

Stores data readings or messages received from IoT devices. Each record includes the timestamp of the measurement (measure_timestamp), the device's network identifier (device_dns), an internal device ID (device_id), the type of message that can be actual point (sensor), control instructions, and set points defined in the actuator. The full detail of respective payload is stored as JSON in “msg” attribute.

Entity Relation and Rationale: This table primarily logs data. It relates implicitly to device, unit and zone, capturing the output generated by devices over time. The use of both device_id and device_dns provides flexibility in how devices might report data.

#### 4.1.1.2.3.7 Recipe

**Entity Physical Name:** cea.recipe

Defines a named set of growth instructions. It includes the recipe name, a description. This entity holds the header for a specific growth plan defined in the Recipe Line.

Entity Relation and Rationale:

- **Defines:** recipe_line (via recipe_id in recipe_line). A recipe consists of one or more sequential steps.
- **Executed As:** recipe_run (via recipe_id in recipe_run). Recipes are instantiated as runs within specific units.

#### 4.1.1.2.3.8 Recipe Line

**Entity Physical Name:** cea.recipe_line

Represents a specific step, phase, or sequence within a recipe. Each line defines target environmental conditions for a duration or cycle, including limits for air temperature, CO2, humidity, substrate temperature, and lighting parameters (type, on/off durations). It has a sequence run identifier (recipe_item_seq_id) and name within the parent recipe.

Entity Relation and Rationale:

- **Part Of:** recipe (via recipe_id). This links the step back to its parent recipe definition. The combination of recipe_id and recipe_item_seq_id uniquely identifies a step.
- **Executed During:** recipe_line_cycle_run (via recipe_id and recipe_item_seq_id). The execution of individual cycles within this recipe step is tracked in recipe_line_cycle_run.

#### 4.1.1.2.3.9 Recipe Run

**Entity Physical Name:** cea.recipe_run

Records an instance of a recipe being executed within a specific cea_unit. It captures the start and end times of the overall run, the associated recipe and unit, the run's status (e.g., running, completed, failed), its active status, and creation/update timestamps.

Entity Relation and Rationale:

- **Instance Of:** recipe (via recipe_id). Specifies which recipe definition is being run.
- **Executed In:** cea_unit (via unit_id). Specifies the production unit where the recipe is being executed.

- **Contains:** recipe_line_cycle_run (via recipe_run_id). Tracks the execution of individual cycles belonging to this specific recipe run instance.

#### 4.1.1.2.3.10Recipe Line Cycle Run

**Entity Physical Name:** cea.recipe_line_cycle_run

Tracks the execution of a specific cycle (recipe_item_seq_cycle_num) of a particular recipe line (recipe_id, recipe_item_seq_id) within a specific recipe run instance (recipe_run_id). It records the start and end times for that cycle, its status, and runtime parameters (as JSON). This allows for detailed tracking of progress through multi-cycle recipe steps.

Entity Relation and Rationale:

- **Belongs To:** recipe_run (via recipe_run_id). Links this cycle execution record to the overall recipe run instance.
- **Execution Of:** recipe_line (via recipe_id, recipe_item_seq_id). Specifies which step definition this cycle belongs to. The combination (recipe_run_id, recipe_id, recipe_item_seq_id, recipe_item_seq_cycle_num) uniquely identifies a specific cycle execution within a run.

#### 4.1.1.3 Analytics Services

The Analytics Services component within the Platform Tier's Information Domain is designed to provide users with the tools necessary for data visualization, monitoring, and in-depth analysis of the Controlled Environment Agriculture (CEA) system's performance. It leverages the data collected and stored by the Data Services (see 4.1.1.2) to offer insights into environmental conditions, actuator behaviour, and overall recipe adherence. The primary interface for these services in the prototype is the Dashboard. Future extensions of Analytics Services could include more advanced data science modelling, digital twin simulations, and sophisticated reporting capabilities, building upon the foundational data captured.

##### 4.1.1.3.1 Dashboard

The Dashboard, exemplified in Figure 27, serves as the primary visual interface for monitoring and analysing the operational data from the PFIoT prototype. It is designed to provide a comprehensive overview of specific environmental parameters within selected cultivation units over defined time periods. This dashboard was implemented using Python Flask as the backend framework to handle data requests and processing, while the frontend was constructed using HTML, with Plotly.js utilized for rendering the interactive charts and visualizations.

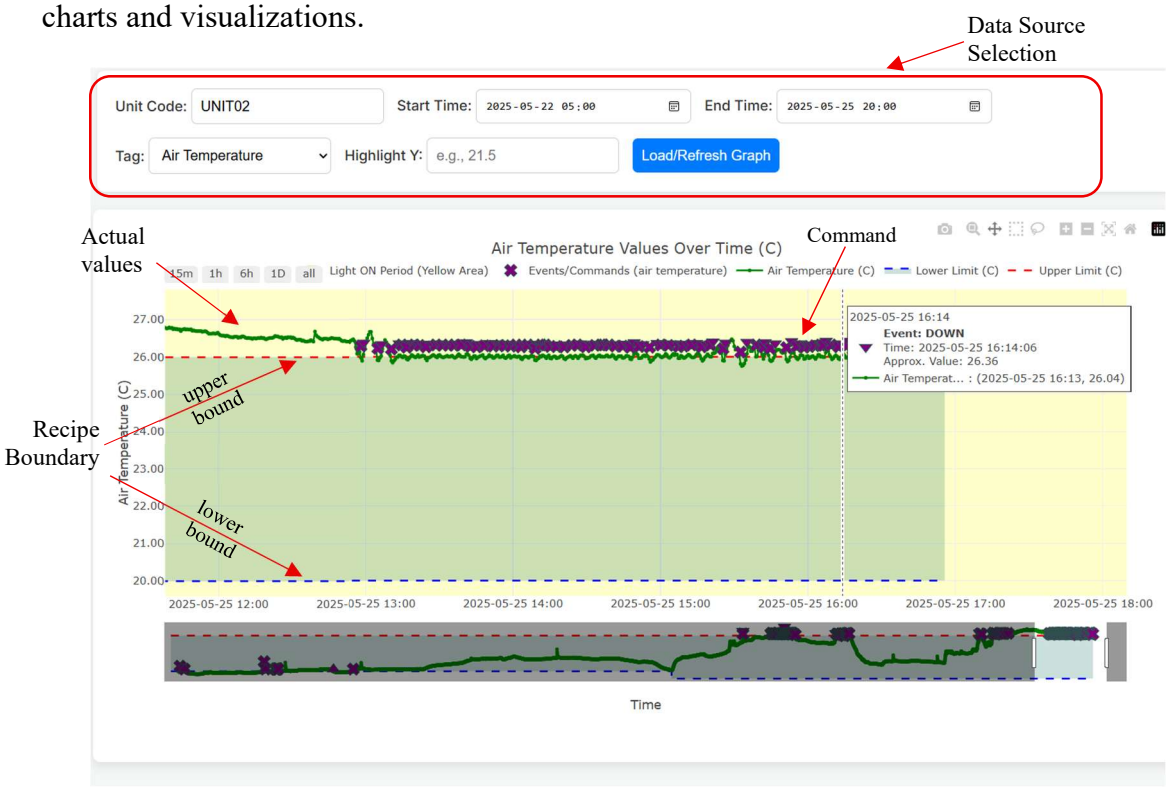



*Figure 27 Dashboard*

Key features of the Dashboard include:

- **Data Source Selection:** Users can precisely define the scope of the data to be visualized through several interactive filters:
    - **Unit Code:** Allows selection of a specific cultivation unit (e.g., "UNIT02" as shown in Figure 27) for which data is to be displayed. This enables focused analysis on individual growing environments.
    - **Tag:** Users can select the specific environmental parameter or measurement tag (e.g., "Air Temperature," "CO2," "Air Humidity") they wish to analyse.
    - **Start Time & End Time:** These date-time pickers allow users to define a specific window for data retrieval and plotting, enabling both real-time monitoring and historical analysis.
- **Visualization of Environmental Data:**
    - **Actual Values Plot:** The core of the dashboard is a time-series line graph that plots the actual sensor readings for the selected Tag (e.g., Air Temperature in °C) over the chosen Start Time to End Time period. This provides a direct visual representation of the environmental conditions experienced within the unit.
    - **Recipe Boundary Limits:** Crucially, the dashboard also plots the Lower Limit and Upper Limit for the selected Tag as defined by the active cultivation recipe for that unit. These are displayed as distinct lines and shaded areas on the graph, allowing users to immediately assess whether the actual environmental conditions remained within the prescribed tolerances of the recipe.
    - **Light ON Period Indication:** To provide context, especially for photosynthetic crops, periods when the grow lights were active within the selected unit are visually highlighted on the graph, often as a distinct background colour (e.g., a yellow area as indicated in Figure 27). This helps correlate environmental changes with lighting cycles.

- **Control Command Overlay:**

The dashboard displays events or commands that were issued by the Environment Control Agent (the run_agent() function detailed in 4.1.1.2.1) for the selected Tag. As shown in Figure 27 for "Air Temperature," when a command such as "DOWN" is issued, an event marker is placed on the graph. This marker typically includes:

- The **type of event/command** (e.g., UP, DOWN, ON, OFF).
- The **timestamp** of when the command was issued.
- The **approximate actual value** of the Tag at or around the time the command was triggered.

This feature provides critical traceability, allowing users to see how the control system responded to deviations from the setpoints and to analyse the effectiveness and timing of these control actions.

### 4.1.2 Operations Domain

The Operations Domain, as conceptualized within the Platform Tier of the PFIoT architecture (refer to Figure 14), encompasses the set of functionalities dedicated to the direct management, execution, and orchestration of cultivation processes. This domain acts as the bridge between the strategic definitions of recipes and schedules and their tactical implementation within the physical growing environments. It is responsible for ensuring that cultivation plans are carried out efficiently, consistently, and in accordance with predefined protocols. Key aspects include managing the lifecycle of cultivation recipes, scheduling their execution in specific production units, and overseeing the control logic that governs the environmental parameters. This domain works in close conjunction with the Information Domain (which provides data and analytics) and the Edge Tier (which executes physical control actions).

#### *4.1.2.1 Operations Management*

Operations Management forms a critical sub-component of the Operations Domain, focusing specifically on the tools and processes required for the effective planning, execution, and monitoring of day-to-day cultivation activities. It translates high-level

production goals into actionable tasks and ensures that the necessary resources and configurations are in place. This includes the detailed definition and administration of cultivation recipes, the scheduling of these recipes across various production units, and the real-time control and adjustment of environmental parameters based on these recipes. The goal of Operations Management is to streamline workflows, ensure reproducibility of results, and provide the necessary oversight to maintain optimal growing conditions. The following subsections will detail key functionalities within Operations Management as implemented in the prototype, such as Recipe Management.

#### 4.1.2.1.1 Recipe Management

The CEA platform employs a recipe-driven approach to operations management, ensuring precise, consistent, and reproducible cultivation protocols for various organisms, such as plants and fungi. This methodology is crucial for standardizing growth processes and achieving predictable outcomes.

Recipe management is implemented using a relational database (PostgreSQL), which serves as a centralized repository for all cultivation parameters, environmental setpoints, and detailed scheduling information. The core of this system is built around two primary entities: **Recipe** and **Recipe Line** (also referred to as recipe detail stages).

**Recipe Entity (cea.recipe)**

The Recipe entity defines the overall cultivation plan for a specific species or variant. Each recipe has a unique identifier and a descriptive name.

**Key Fields:**

- recipe_name (Text): The name of the recipe (e.g., "Basilico", "Pleurotus ostreatus"), used as the identifier when scheduling a production recipe.

Example from Figure 28:

- recipe_id: 1
- recipe_name: "Basilico"
- recipe_description: "Recipe for Basilico (*Ocimum basilicum*)"

**Recipe Line Entity (Recipe Details)**

The Recipe Line entity details the specific environmental conditions and schedules for each distinct phase or stage within a given recipe. A single recipe can consist of multiple sequential recipe lines, each representing a different part of the cultivation cycle (e.g., germination, vegetative growth).

**Key Fields:**

- recipe_item_seq_id: Defines the sequential order of phases (and their associated setpoints) within the recipe.
- cycle_number: Defines the number of cycles where specified environmental setpoints are active. The duration of each cycle is defined by the sum of light_on_minutes and light_off_minutes.
- light_on_minutes: Defines the duration, in minutes, that the specified light_type (e.g., RED) is active each day.
- The remaining attributes define the boundary limits (e.g., upper and lower thresholds) within which a given environmental parameter should be maintained.

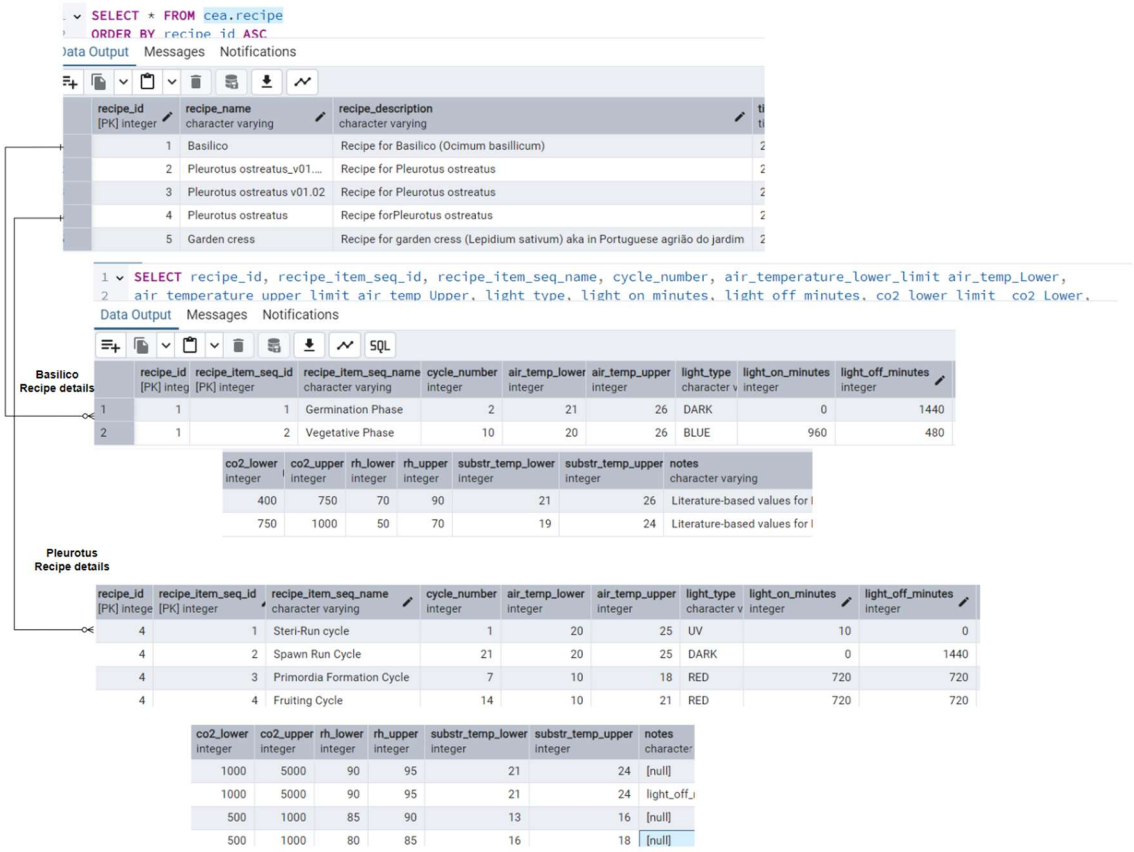



*Figure 28 Recipe management.*

This recipe configuration data structure is used to implement the execution of a recipe by the "Recipe Scheduler and Control" component (4.1.2.1.2 Recipe scheduler and control).

#### 4.1.2.1.2 Recipe scheduler and control

The "Recipe Scheduler and Control" functionality is primarily implemented by the run_recipe.py Python script (see Appendix B). This script is responsible for orchestrating the execution of a defined cultivation recipe within a specific production unit. It acts as the bridge between the recipe definitions stored in the database and the real-time control actions performed at the Edge Tier, typically via MQTT messaging.

The script is invoked from the command line, specifying the target unit and the recipe to be executed, for example:

```
python3 -u /home/svieira/repos/CEA/platform/scripts/run_recipe.py UNIT01 "Pleurotus ostreatus"
```

**High-Level Logic of run_recipe.py:**

1. **Initialization:**
    - The script begins by loading necessary environment variables, which include credentials for database access (host, database name, user, password) and MQTT broker details (URL, port, project name).
    - It accepts two command-line arguments: unit_code (e.g., "UNIT01") and recipe_name (e.g., "Pleurotus ostreatus").
2. **Database Interaction & Run Setup:**
    - It establishes a connection to the database where the PF data model is, using the loaded credentials.
    - The script checks are the safe conditions to run a recipe is a given unit are met before it starts the execution (e.g. unit availability to run).
    - The overall status of this recipe_run is updated to 'Running' in the database.
3. **Recipe Phase and Cycle Execution:**

- The script fetches the defined sequence of recipe lines (phases or stages) associated with the recipe_name.
- It then iterates through each phase (recipe_item_seq_id) of the recipe. For each phase:
    - The detailed environmental parameters (run_params) and the number of daily cycles (cycle_number) for that phase are retrieved.
    - The script enters an inner loop to execute each daily cycle for the current phase.
    - **State Management:** Before executing a cycle, it checks if this specific cycle (identified by recipe_run_id, recipe_item_seq_id, and recipe_item_seq_cycle_num) has already been completed. If so, it skips to the next cycle. Otherwise, it creates or updates a record for the current cycle, marking its status as 'Started' and then 'Running'.
    - **Agent Invocation (cea.run_agent):** The core control logic for the cycle is delegated to function cea.run_agent(). This function takes the unit_code, the run_params (containing setpoints like temperature, humidity, light schedule, CO2 levels), and the cycle's start time. It is responsible for translating these parameters into actions, publishing MQTT messages to topics monitored by the Edge Tier devices in the specified unit_code. The run_agent function blocks or waits until the cycle duration (derived from the sum of light_on_minutes  light_off_minutes) is complete.
    - **Cycle Completion:** Once cea.run_agent finishes, the script updates the status of the current cycle to 'Completed' in the database.

4. **Recipe Completion & Error Handling:**
    - After all phases and their respective cycles have been successfully executed, the overall status of the recipe_run is updated to 'Completed'.

- The script includes robust error handling. If any exception occurs during its execution, the recipe_run status is updated to 'Failed', an error message is logged, and the script exits with a non-zero status code.

Detailed Flow Swimlane Diagram describing the entire process can be found in Appendix Figure B.1.

#### *4.1.2.2 Platform Management*

##### 4.1.2.2.1 Device and Metadata Management

Within this system, device and metadata management is implemented through two primary entities: the Device entity and the Component entity.

The Device entity serves the crucial purpose of registering all devices deployed within a specific zone_id, which in turn belongs to a larger "unit." This entity is the central repository for essential device metadata. Such metadata includes, but is not limited to, the device_type (e.g., Control, Sense), model designation, a unique serial_number (which could be a MAC address), and its dns_name for network identification.

Each device registered in the system can be associated with one or more sub-parts or functionalities, which are represented in the Component entity. This entity details the components connected to or integrated within a device.

To illustrate the relationship and utility of these entities, consider the following examples (Figure 29):

A device with device_id 1, designated as a CONTROL type device, might possess a component identified by component_id 8. This component could be an ACTUATOR type, specifically an 8-channel relay. The component entity would store its respective control parameters, which are used for mapping high-level control commands to the low-level activation or deactivation of board pins.

Another example is device_id 8, classified as a SENSE type device. This device could have an associated camera component, such as an ov2640 model. The component entity would, in this case, store the necessary parameters for a REST API call, enabling the system to instruct the camera to capture images.

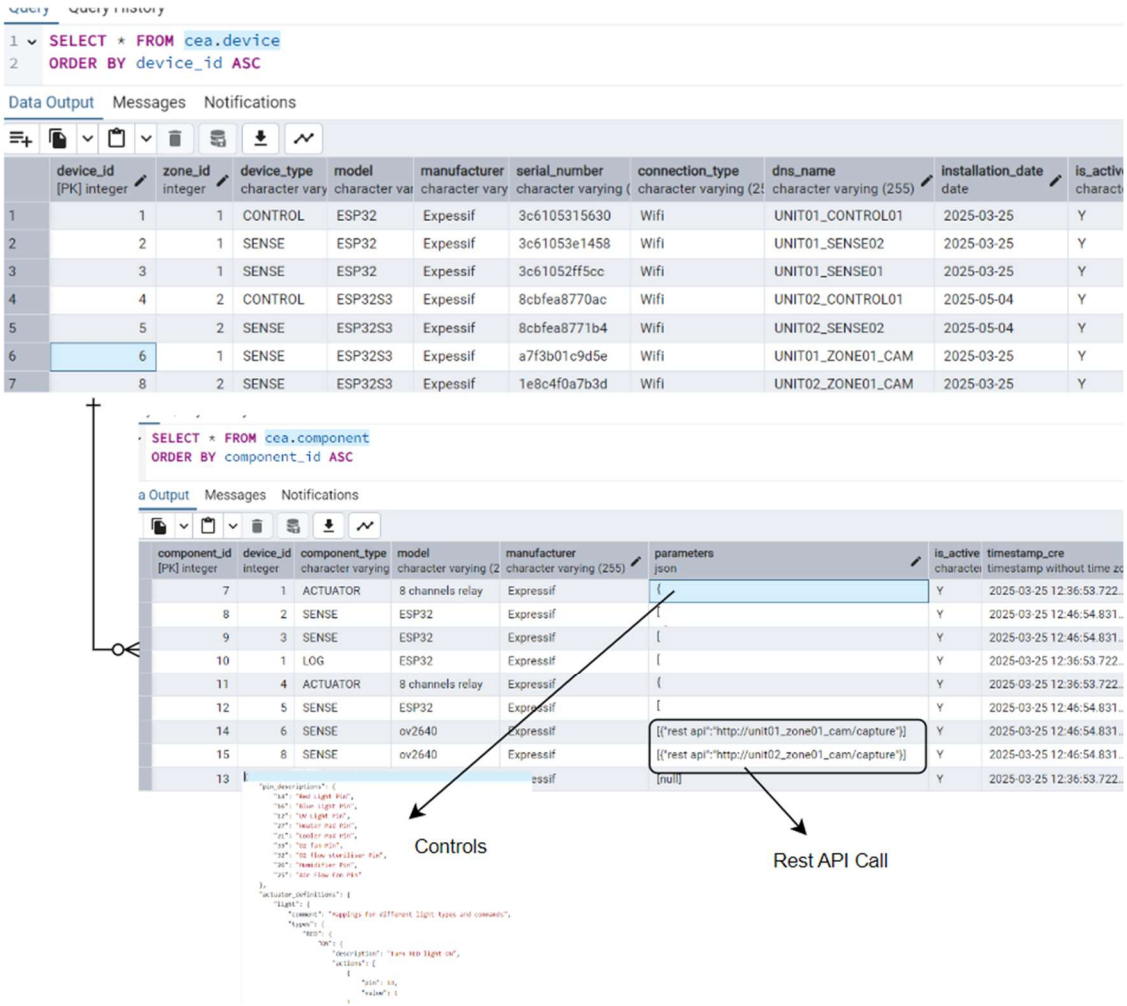



*Figure 29 Device and Metadata Management*

This structured approach to data management, separating devices from their constituent components and detailing their respective metadata and parameters, offers significant advantages. It greatly simplifies the ability to generically and programmatically implement various logic operations. For instance, developing routines to periodically capture pictures from all camera components or allows to update the control logic for actuator components can be done more efficiently, and systematically. This externalization of device logic facilitates easier updates, centralized management, and more flexible system automation. Additionally, this structure provides to the control feedback loop awareness to the feedback control loop (cea.run_agent) to which controller the commands should be send to.

#### 4.1.2.2.2 Measurement and Control Monitoring

A core design principle of the CEA platform is to ensure full traceability for all environmental variables, control commands, and actuations (i.e., actuator pin activations/deactivations). This comprehensive traceability is fundamental for monitoring, debugging, and optimizing the controlled environment.

All system integration and communication are orchestrated through a central message broker (Mosquitto). This MQTT hub serves as the conduit for interactions between various system components. Sensed environmental variables from edge devices are published to the broker. Decision-making processes, supported by the "Recipe Scheduler and Control" and the "Environment Control Agent," subscribe to relevant topics, analyse the data, and subsequently publish control commands back to the broker. These commands are then consumed by the respective edge devices to enact changes.

To further enhance system robustness and provide a clear audit trail, the "Message Processing and Routing" component (detailed in section 4.1.1.1.2) is decoupled from other CEA components. This specialized mechanism continuously captures all activities within the feedback control loop. These activities are then materialized and persisted in a generic entity named cea.measurement (see 4.1.1.2.3.6 Measurement).

The Measurement and Control Monitoring capability is implemented through this cea.measurement entity. It is designed to store various message types that form part of the feedback control loop, ensuring that every significant event is recorded. The key message types include (Figure 30):

**AP (Actual Point)**: Represents sensed data from the environment (e.g., temperature, humidity readings from sensors).

**CT (Control)**: Denotes control commands issued by the decision-making logic (e.g., commands sent to edge actuators).

**SP (Set Point)**: Confirms the state or set point implemented by an actuator as a direct result of a received command (e.g., a relay pin being activated).

This data structure allows for a granular and chronological understanding of the system's behaviour.

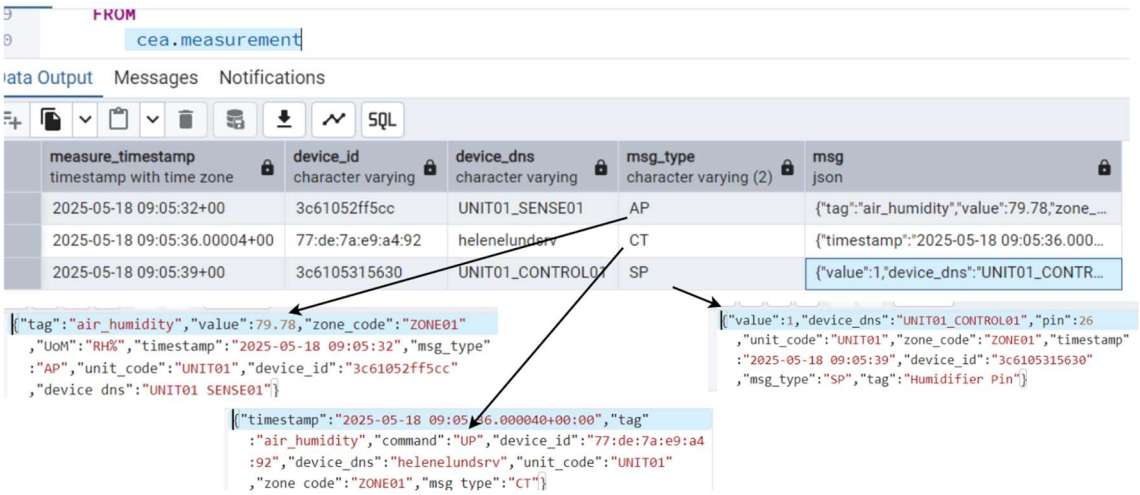



*Figure 30 Measurement and control monitoring*

**Example of Traceability in Action:**

The traceability is evident in the following example depicted in **(**Figure 30**)**, illustrated by records from the cea.measurement entity:

1) Actual Point (AP) - Sensed Data: At 2025-05-18 09:05:32+00, the device UNIT01_SENSE01 (ID: 3c61052ff5cc) reported an air humidity level of 79.78% RH in ZONE01. This is logged as an 'AP' message.

   msg: *{ "tag":"air_humidity", "value":79.78, "zone_code":"ZONE01", "UOM":"RH%", "timestamp":"2025-05-18 09:05:32", "msg_type":"AP", ...}*

2) Control (CT) - Command Issued: Subsequently, at 2025-05-18 09:05:36.00004+00, the Environment Control Agent (running in device helenelundsrv) issued a command. For the air_humidity tag in ZONE01, the command sent was 'UP'. This is logged as a 'CT' message.

   msg: *{ "timestamp":"2025-05-18 09:05:36.000040+00:00", "tag":"air_humidity", "command":"UP", ..., "msg_type":"CT" }*

3) Set Point (SP) - Actuation Confirmation: Following the command, at 2025-05-18 09:05:39+00, the control device UNIT01_CONTROL01 (ID: 3c6105315630) reported that the Humidifier Pin (pin 26) was activated (set to value: 1). This is logged as an 'SP' message, confirming the actuator's response to the control command.

   msg: *{ "value":1, "device_dns":"UNIT01_CONTROL01", "pin":26, ..., "tag":"Humidifier Pin", "msg_type":"SP" }*

This sequence demonstrates the feedback loop: a sensed environmental condition (high humidity) triggered a control decision (command 'UP'), which resulted in a specific actuation (Humidifier pin activated). This level of detailed logging is invaluable for analysing system performance, diagnosing issues, and ensuring accountability of control actions.

## 4.2 Edge Tier Implementation

Positioned closest to physical devices such as sensors and actuators, this layer is responsible for real-time data acquisition, local processing and filtering, and the execution of immediate control commands. These edge functions were implemented using MicroPython [151], which is a lean and efficient Python 3 implementation featuring a small subset of the standard library and is specifically optimized for the resource constraints of microcontrollers. The selection of MicroPython was motivated by its ease of learning and the robust support available from the extensive Python contributing community, which significantly aids future development and supportability.

The Edge Tier constitutes the critical interface between the digital control system and the physical cultivation environment. Its primary responsibilities within this prototype encompass real-time data acquisition from diverse environmental sensors (e.g., temperature, humidity, CO2, etc), execution of immediate control actions based on the active growth recipe segment (e.g., adjusting light intensity, activating ventilation), performing preliminary data filtering and aggregation to reduce network load, and ensuring secure, reliable data transmission to the Platform Tier via the MQTT protocol.

The Control Domain in this three-tier IoT architecture is a pivotal component responsible for managing and executing the direct interactions with the physical environment. It bridges the gap between the higher-level application logic (often residing in the Platform or Edge Gateway) and the physical devices (sensors and actuators) deployed in the field. A key design principle within this implementation is the separation of concerns between actuation and control logic. This means that the low-level device actuation mechanisms are distinct from the higher-level control decision-making processes, rather than being tightly coupled within the same application or micro-controller program. This separation enhances modularity, scalability, and maintainability of the system.

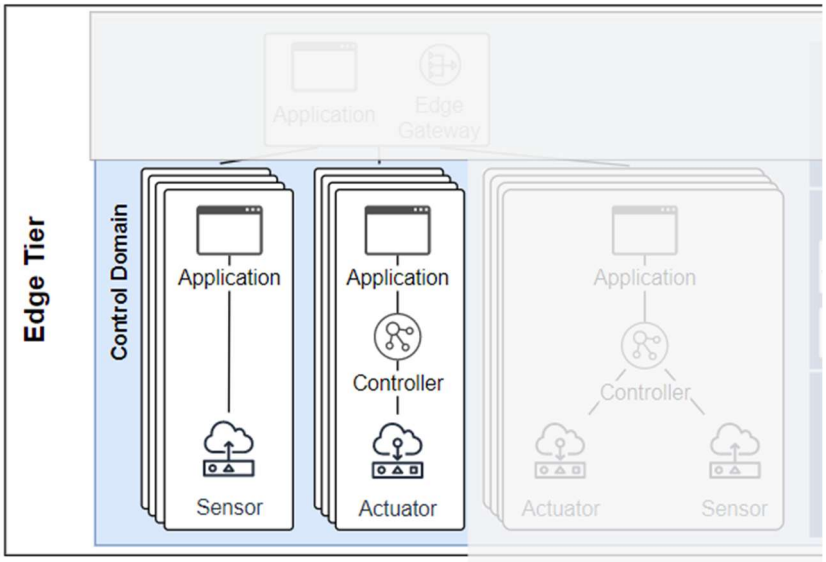



*Figure 31 Control domain patterns implemented in the Prototype*

The Control Domain encompasses the applications and controllers that directly interface with sensors and actuators. The primary physical interface components within this domain are Sensors, which gather information, and Actuators, which perform actions. The control logic, often residing in controllers or edge applications, utilizes data from sensors to make decisions and command actuators. The prototype implementation as illustrated in Figure 31 the Control Domain considered the separation of Sensor and Actuator applications.

#### *4.2.1.1 Sense Component*

The Sense component within the Control Domain represents the software mechanisms that enable the system to gather data about the environment and the processes within it. These are the "senses" of the IoT system, providing the raw information necessary for monitoring and decision-making. Sensors are devices or software interfaces that detect and respond to diverse types of input from the physical environment. These inputs can include temperature, humidity, $CO_2$, etc and are made available through the Sensor Application depicted in Figure 32.

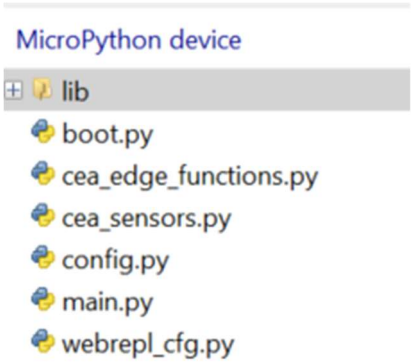



*Figure 32 Sense Application*

The sense application comprises:

- **lib** – Contains libraries from the MicroPython community required by the sense application. Examples include the MQTT library or the SCD30 (CO2 sensor) library.
- **boot.py** – This script is executed at startup and implements one-time settings required for the implemented logic. Examples include network configuration (DNS name, network connection) or setting the time (e.g., to UTC).
- **cea_edge_functions.py** – Contains libraries specifically implemented for this project.
- **cea-sensors.py** – Contains various libraries required for the sensors used in the current implementation.
- **config.py** – Contains device-specific configurations, such as network authentication details, MQTT topic names, unit code, zone code, etc.
- **main.py** – Contains the logic implemented by the sensor application. It typically consists of reading sensor values at a predefined frequency and sending them as MQTT messages to the MQTT broker.
- **webrepl.cfg** – Configures the device to be accessible remotely.

#### 4.2.1.2 Actuator Component

The Actuator component within the Control Domain represents the software mechanisms that enable the system to effect changes in the environment or control

physical processes. These are the "hands" of the IoT system, translating digital commands into tangible actions.

The actuator application is the software interface that receives commands from the control logic and translates them into physical actions. In this context, several examples are presented such as  relays to turn lights on or off, heaters, coolers, etc.

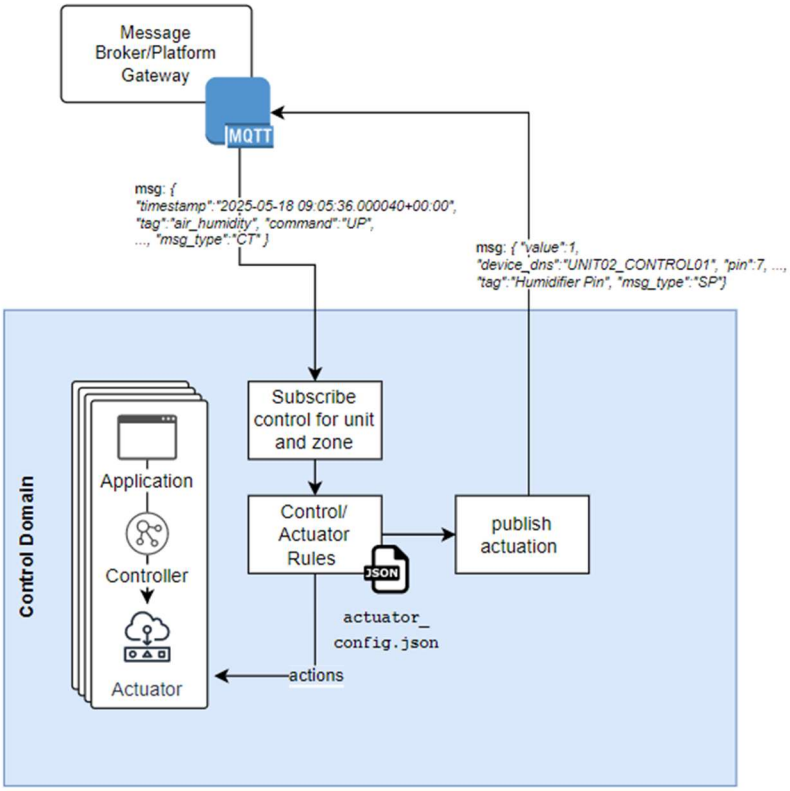



*Figure 33 Actuator logic.*

As depict in the Figure 33 the control device subscribes to a topic relevant to its unit and zone. As soon as it receives a command from the control logic, it translates that command into actuator instructions. The mechanism for applying this translation is based on an **actuator_config.json** file that contains the mapping between a command and the corresponding pin activations.

As shown in the example in Figure 34 if an air_humidity command is "UP", the actuator will activate pin 7 (which must be connected to a humidifier relay).

For full feedback control loop traceability, the control device then publishes the action taken (e.g., pin 7 activated) back to the MQTT broker.

```
{
  "pin_descriptions": {
    "46": "UV Light Pin- placeholder",
    "3": "RED Light Pin-placeholder",
    "14": "Blue Light Pin",
    "9": "Heater Pad Pin -placeholder",
    "13": "Cooler  Pin",
    "12": "CO2 fan Pin",
    "11": "CO2 flow steriliser Pin",
    "7": "Humidifier Pin",
    "10": "Air Flow fan Pin"
  },
  "actuator_definitions": {
    "light": {...},
    "air_temperature": {...},
    "co2": {...}
    },
    "air_humidity": {
      "comment": "Mappings for Air Humidifier(26)/Airflow(25) commands",
      "commands": {
        "UP": { "description": "Activate Air Humidifier", "actions": [ { "pin": 7, "value": 1 }, { "pin": 10, "value": 0 } ] },
        "DOWN": { "description": "Dehumidify using Air Flow Fan", "actions": [ { "pin": 7, "value": 0 }, { "pin": 10, "value": 1 } ] },
        "OFF": { "description": "Deactivate Air Humidifier and Air Flow Fan", "actions": [ { "pin": 7, "value": 0 }, { "pin": 10, "value": 0
      }
    },
    "substrate_temperature": {...}
    }
  }
}
```


*Figure 34 Actuator config.*

The control application comprises (Figure 35):




*Figure 35 Control Application*

- **boot.py** – This script is executed at startup and implements one-time settings required for the implemented logic. Examples include network configuration (DNS name, network connection) or setting the time (e.g., to UTC).
- **config.py** – Contains device-specific configurations, such as network authentication details, MQTT topic names, unit code, zone code, etc.
- **main.py** – Contains the logic implemented by the control application. It typically consists of receiving command, apply actuation.
- **webrepl.cfg** – Configures the device to be accessible remotely.

Physical Prototype

The prototype installed consisted of two chambers, unit01 (Figure 37) and unit02 (Figure 38), respectively configured to host fungi and plants (Figure 36).

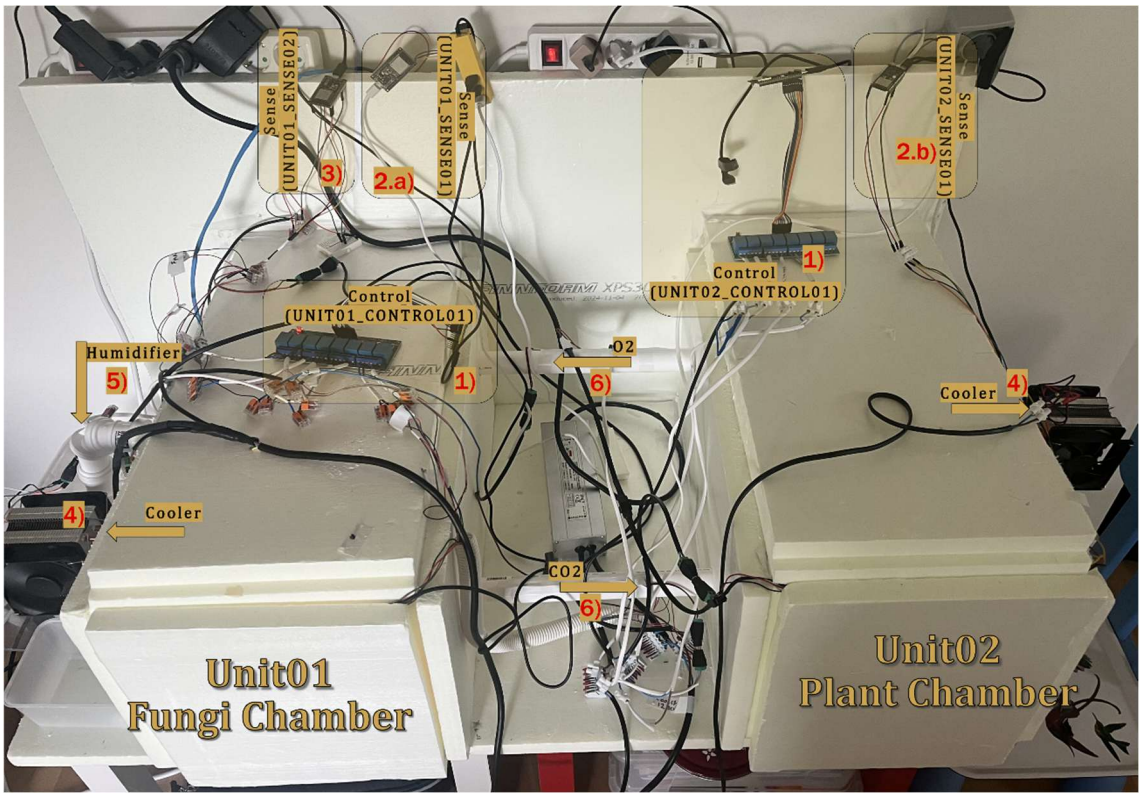



*Figure 36 Prototype - physical installation.*

Figure 36 Legend:

1) Controller, with a ESP32 MCU and 8-channel relay

2.a) ESP32 MCU with SCD30 sensor for humidity, temperature and $CO_2$

2.b) ESP32 MCU with SCD41 sensor for humidity, temperature and $CO_2$

3) ESP32 MCU with DS18B20 for temperature sensor.

4) Peltier Cooler

5) Humidifier nebuliser

6) Air flow with ultraviolet light for sterilisation

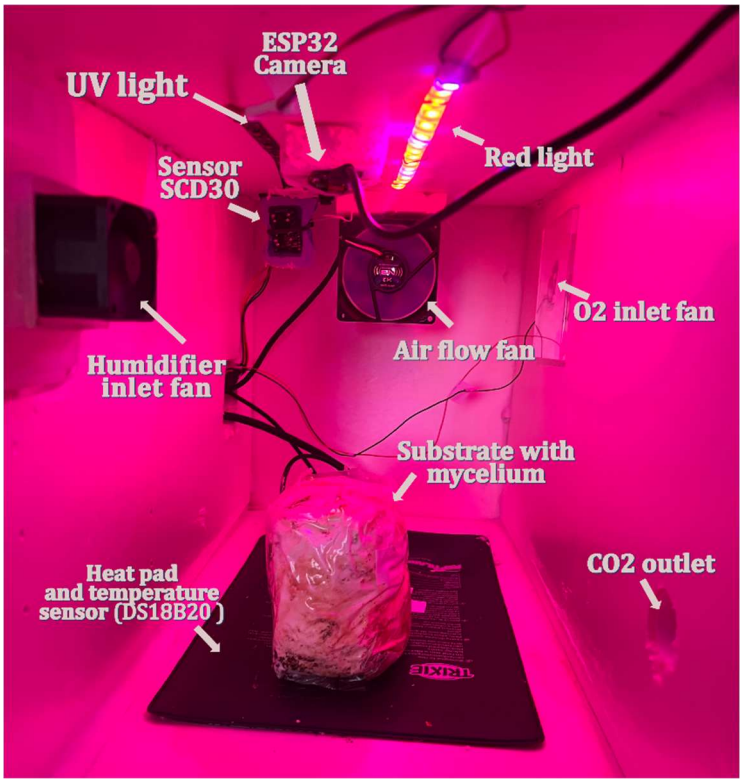



*Figure 37 Mushroom chamber.*

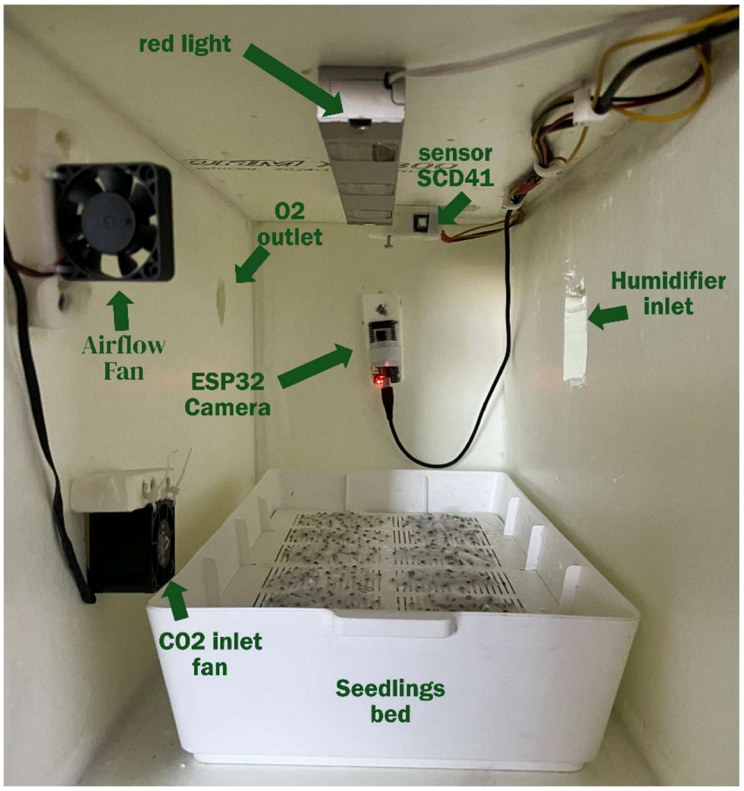



*Figure 38 Plant chamber.*

#### 4.2.1.3 Sensors and actuators

The Edge Tier of the prototype's PFIoT architecture is deployed within both the plant and fungal cultivation chambers. It provides localized, real-time sensing and control capabilities, enabling independent management of each environment. Each chamber, constructed as a cuboid with dimensions of 30 cm high x 30 cm deep x 50 cm wide, houses a dedicated set of sensors and actuators:

- **The ESP32 microcontroller** serves as the primary interface between the physical environment and the PFIoT architecture within each cultivation chamber. While capable of executing complex control algorithms, this prototype utilizes the ESP32 primarily for sensing and actuation, streamlining the Edge Tier and centralizing control logic within the Platform Tier.



*Figure 39 ESP32-S3-DevKitC-1-N8R8*



*Figure 40 FireBeetle 2 Board ESP32-S3 (N16R8) AIoT Microcontroller with Camera*

- **Sensirion SCD30**: is a compact, high-accuracy CO2 sensor module utilizing Non-Dispersive Infrared (NDIR) technology. It integrates precise temperature and humidity sensors and offers reliable CO2 measurements from 400 to 10,000

ppm with an accuracy of ±(30 ppm + 3%). This sensor is used to measure air parameters in both chambers.



*Figure 41 Sensirion SCD30 (https://sensirion.com/products/catalog/SCD30)*

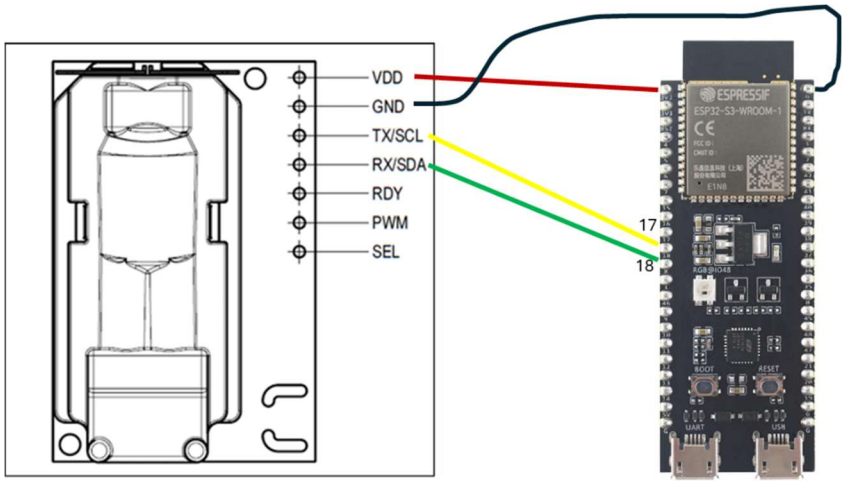



*Figure 42 Pin-out of the SCD30 and ESP32*

- **Sensirion SCD41**: is a miniature, high-accuracy CO2, temperature, and humidity sensor module that utilizes Sensirion's patented Photoacoustic NDIR (Non-Dispersive Infrared) sensor technology (PASens®). It integrates precise temperature and humidity sensors, providing reliable CO2 measurements over a range of 400 ppm to 5,000 ppm with an accuracy of ±(40 ppm + 5% of reading). Due to its compact size (10.1 x 10.1 x 6.5 mm³), it is well-suited for various applications requiring the monitoring of indoor air quality parameters.

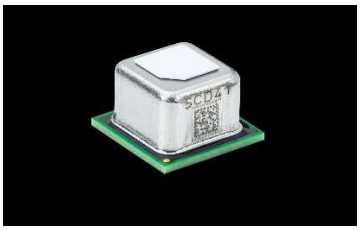


*Figure 43 Sensorion SCD41 (https://sensirion.com/products/catalog/SCD41)*

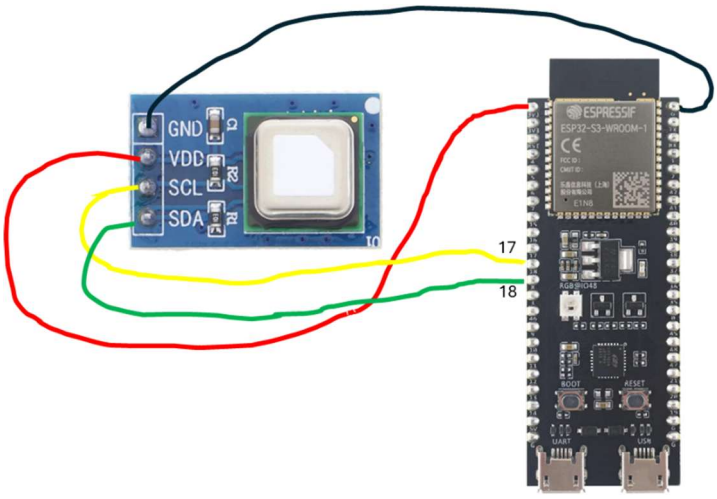



*Figure 44 Pin-out of the SCD41 and ESP32*

- **Digital temperature sensor**. This Waterproof 1-Wire DS18B20 provide reading -10°C to +85°C with accuracy ±0.5°C. This sensor is used to monitor the temperature of substrate and nutritional solution.



*Figure 45 DS18B20 Digital temperature sensor.*

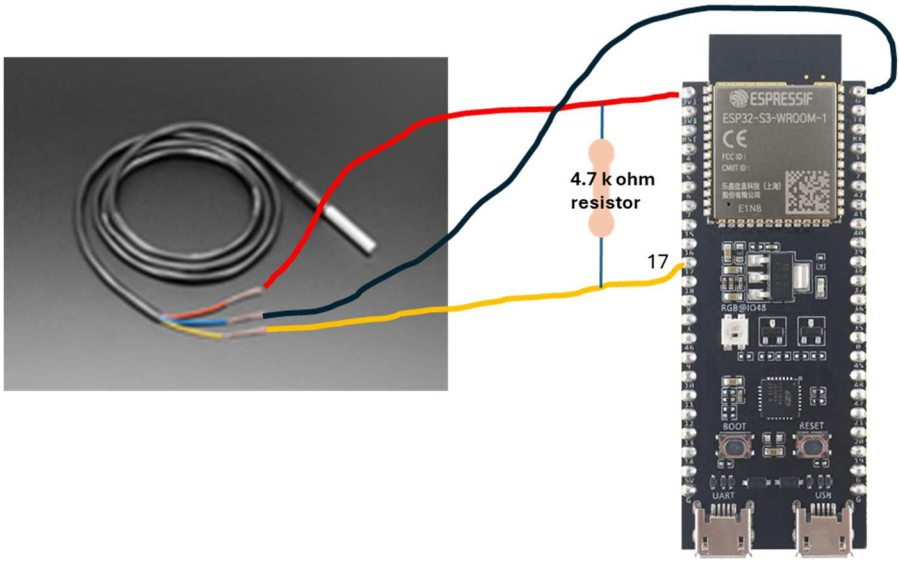



*Figure 46 Pin-out of the DS18B20 and ESP32*

- **UVC Ultraviolet Germicidal Lamp Strip,** it is a flexible LED strip utilizes high-intensity Ultraviolet-C (UVC) light, specifically targeting the germicidal wavelengths of 270-280nm. Designed for effective sterilization by damaging the DNA and RNA of bacteria, viruses, mold spores, and other pathogens. This are applied to the chamber's ceiling for its sterilization**.** Additionally, strips are positioned within the airflow connections between chambers to sterilize the air as it circulates, significantly minimizing the risk of cross-contamination between the different chamber environments.

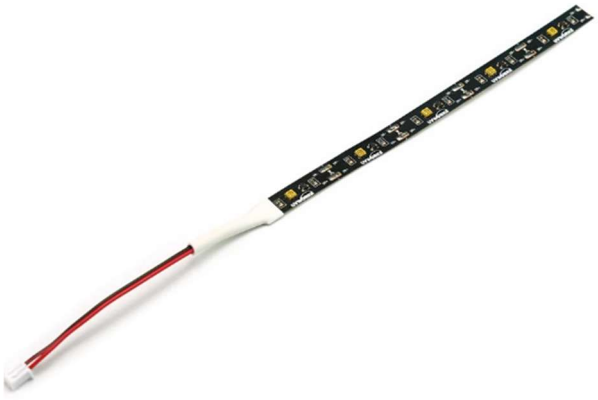


*Figure 47 UVCC light (www.dfrobot.com/product-2746.html)*

- **Fan (PC fan):** A standard PC fans were used to ensure homogeneity of air temperature and humidity within the chambers, facilitate gas exchange between the mushroom and plant chambers, and provide fresh air exchange.



*Figure 48 fan for chamber air interexchange (https://mou.sr/3RVHIjN)*




*Figure 49 Flow for humidity increase flow.*

- **Heat Pad:** A heat pad provides supplemental heat when necessary to maintain the desired temperature setpoint, particularly during periods of low ambient temperature.




*Figure 50 Lerway Seedling heat mat 30w Heat pad (https://amzn.eu/d/8PxrI2m)*

- **Humidifier (Ultrasonic Nebulizer TDK):** NB-80E-01-H an ultrasonic nebulizer to increases humidity levels within the chambers by generating a fine mist of water droplets, promoting optimal plant transpiration and fungal growth.



*Figure 51 Nebuliser (https://mou.sr/44uL70r)*

- **Cooler (12V 120W Peltier Cooler):** A Peltier cooler provides active cooling to counteract heat generated by lighting or metabolic processes, ensuring that temperatures remain within the desired range.



*Figure 52 Cooler*

- **Grow LED Strip**, used in both mushroom and plant chambers. It implements a Red Blue 3:1 ratio (625-660 nm).



*Figure 53 Grow light.*

- **Switch (relay)** module acts as a safe, controllable power switchboard. It allows control system ESP32 to independently turn on and off up to eight different devices for environment control, such as grow lights, water pumps, nutrient pumps, fans, or solenoid valves.

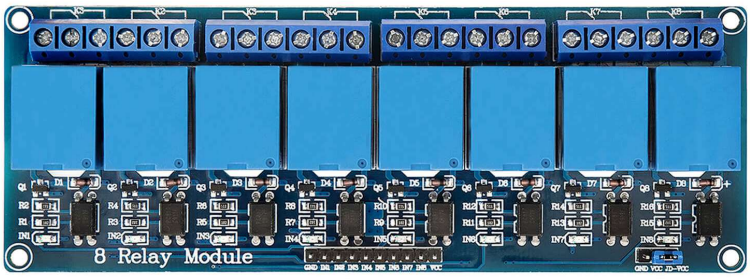



*Figure 54 8-Channel relay (https://www.adafruit.com/product/381)*

# Chapter 5 Results and discussion

## 5.1 Introduction

This research aimed to develop and evaluate a Controlled Environment Agriculture (CEA) system prototype based on the proposed Plant Factory Internet of Things (PFIoT) architecture. Key objectives included demonstrating the system's capacity to support the simultaneous operation of multiple, independent cultivation units, each running distinct environmental recipes, and to facilitate inter-unit resource exchange, specifically CO2 and O2, between a fungal and a plant cultivation chamber.

Overall key findings:

- The developed prototype successfully demonstrated the parallel operation of Unit 01, cultivating *Pleurotus ostreatus* (Oyster Mushroom), and Unit 02, cultivating *Ocimum basilicum* (Basil), each adhering to its specific pre-defined environmental recipe.
- The system facilitated the controlled interchange of atmospheric gases (CO2 from the fungal unit to the plant unit, and O2 in the reverse direction) between the two units.
- Operational evaluations identified specific limitations, notably concerning the cooling efficacy of the Peltier thermoelectric actuators under certain thermal loads and the characteristic behaviour of the implemented rule-based control system when subjected to external environmental disturbances or thermal generation from lightning, often resulting in operation at the defined boundary limits of the control parameters.

This chapter presents the experimental results obtained from the prototype's operation. It begins by evaluating the system's performance in managing parallel, independent cultivation units, including the control of key environmental parameters such as temperature, humidity, and $CO_2$ levels. Subsequently, the specifics of the $CO_2$/$O_2$ exchange mechanism and its observed dynamics are presented. The chapter then delves into an analysis of actuator performance, focusing on the Peltier cooling units and humidity control actuators, and examines the response of the rule-based control system to external disturbances. Each section includes a presentation of relevant data, often in

the form of graphical charts, followed by a discussion of the findings, their implications, and any encountered limitations. The chapter concludes with an overall discussion synthesizing these results in the context of the research objectives.

## 5.2 System Performance: Parallel Operation of Independent Cultivation Units

This section presents the results demonstrating on a temporal subset the system's capability to simultaneously manage distinct environmental conditions for *Pleurotus ostreatus* in Unit 01 and *Ocimum basilicum* in Unit 02, each following its unique cultivation recipe. The time period used for exemplification purposes is the same for both Units.

### 5.2.1 Unit 01: *Pleurotus ostreatus* (Oyster Mushroom) Cultivation

Unit 01 was dedicated to the cultivation of *Pleurotus ostreatus*, following the multi-stage recipe detailed in 4.1.2 (specifically, recipe ID 2 Figure 28) and specified in Table 3. Environmental parameters including air temperature, relative humidity, and $CO_2$ concentration were monitored and controlled by the PFIoT system.

| Recipe Id | Recipe Item Sequence | Recipe Item Sequence name | Number of Cycles ("days") | Air Temperature | | Light | | | CO2 | | Humidity | | Substrate Temperature | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | lower limit | upper limit | Type | On (min.) | Off (min.) | lower limit | upper limit | lower limit | upper limit | lower limit | upper limit |
| 2 | 1 | Spawn Run | 21 | 20 | 25 | DARK | 0 | 1440 | 1000 | 5000 | 90 | 95 | 21 | 24 |
| 2 | 2 | Primordia Formation | 7 | 10 | 18 | BLUE | 720 | 720 | 500 | 1000 | 85 | 90 | 13 | 16 |
| 2 | 3 | Fruiting | 14 | 10 | 21 | BLUE | 720 | 720 | 500 | 1000 | 80 | 85 | 16 | 18 |

*Table 3 Recipe for "Pleurotus ostreatus"*




*Figure 55 Time-series plot of air temperature in Unit01.*

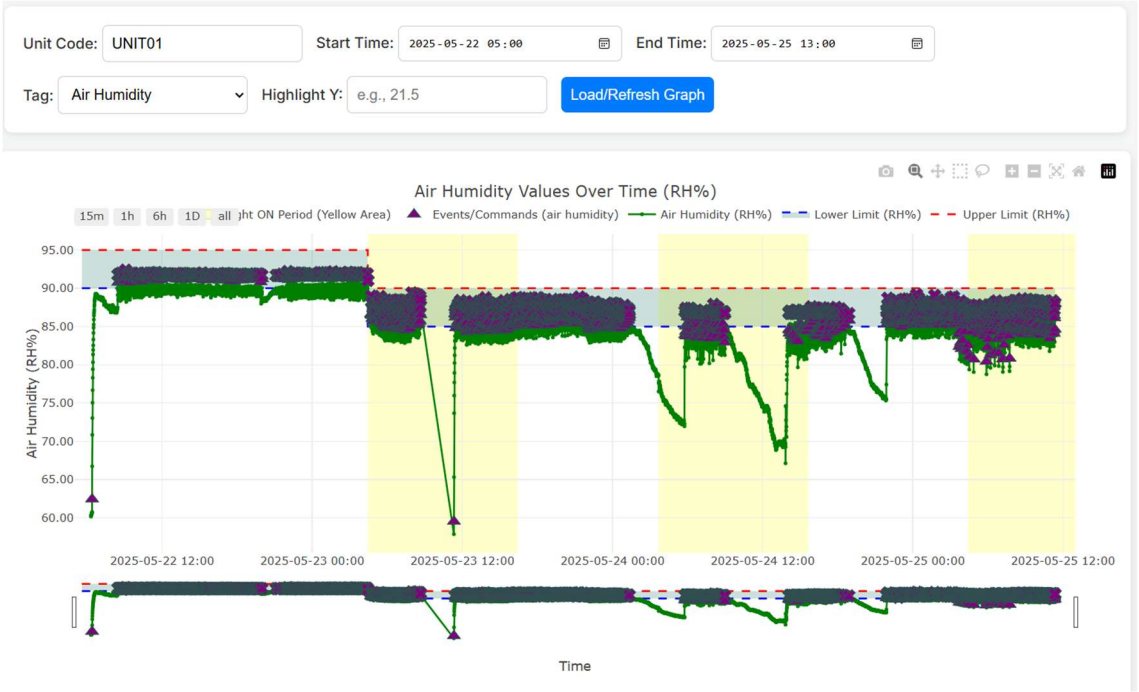



*Figure 56 Time-series plot of relative humidity in Unit 01*

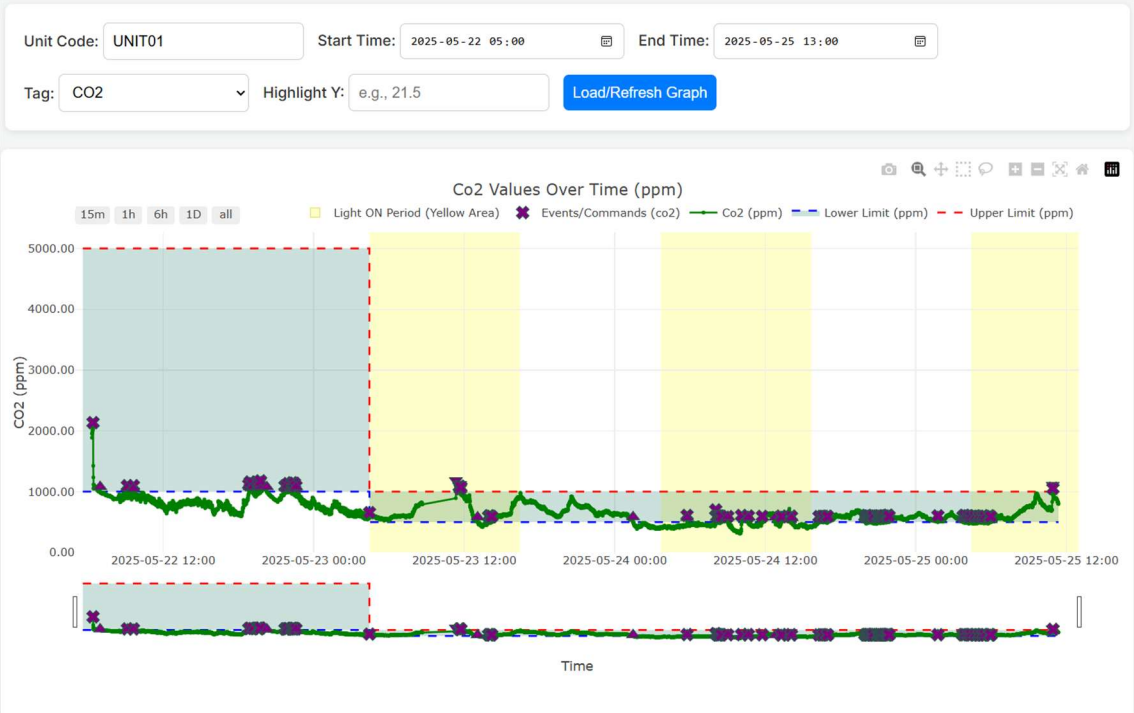



*Figure 57 Time-series plot of CO2 concentration in Unit 01*

The environmental control within Unit 01, managed by the rule-based system, generally demonstrated stability in adhering to the recipe setpoints. Figure 55 shows that air temperature during the spawn run phase (e.g., targeting 20-25°C prior to 2025-05-23 00:00) was largely maintained within the defined upper and lower limits, though minor fluctuations (approximately ±1-2°C) are observable. These variations are likely attributable to the cycling of heating/cooling elements and the influence of external ambient temperature shifts, as discussed further in section 5.5.

Figure 56 illustrates the system's effectiveness in maintaining high relative humidity levels, critical for mushroom cultivation. During periods corresponding to primordia formation, humidity readings were typically held within 5% of the target setpoints (e.g., 90-95% RH), with the humidifier activating in response to sensor feedback to maintain these conditions. When RH values were below the lower limit it meant that the water repository needed to be filled.

CO2 concentration, depicted in Figure 57, shows the expected natural increase due to mycelial respiration during the initial colonization phase. Subsequently, for stages requiring lower CO2 levels (e.g., fruiting), the control system-initiated ventilation or gas exchange events. The chart shows the system's attempts to manage $CO_2$ within the target bands, though the precision of maintaining a specific low $CO_2$ level is inherently linked

to the efficiency of the air exchange mechanism and the rate of $CO_2$ production by the fungi.

Observed deviations from setpoints across all parameters were often correlated with the activation cycles of actuators or significant external disturbances. For instance, a sudden drop in ambient room temperature could cause the chamber temperature to briefly dip below the lower setpoint before the heating pad could fully compensate. Qualitative observations during the trial period indicated successful mycelial colonization of the substrate and the initiation of primordia when appropriate environmental triggers were applied. These observations, while not a formal biological yield study, suggest that the PFIoT system could provide an environment conducive to fungal development according to the specified recipe.

### 5.2.2 Unit 02: *Ocimum basilicum* (Basil) Cultivation

Unit 02 was configured for the hydroponic cultivation of *Ocimum basilicum*, following the multi-stage recipe detailed in 4.1.2 (specifically, recipe ID 1 Figure 28).the "Basilico" recipe (Table 4 Recipe for "Basilico" ). Key controlled parameters included air temperature, relative humidity, CO2 concentration (with potential enrichment from Unit 01), and a defined photoperiod using LED lighting.

| Recipe Id | Recipe Item Sequence | Recipe Item Sequence name | Number of Cycles ("days") | Air Temperature | | Light | | | CO2 | | Humidity | | Substrate Temperature | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | lower limit | upper limit | Type | On (min.) | Off (min.) | lower limit | upper limit | lower limit | upper limit | lower limit | upper limit |
| 1 | 1 | Germination Phase | 7 | 21 | 26 | DARK | 0 | 1440 | 400 | 750 | 70 | 90 | 21 | 26 |
| 1 | 2 | Vegetative Phase | 28 | 20 | 26 | BLUE | 960 | 480 | 750 | 1000 | 50 | 70 | 19 | 24 |

*Table 4 Recipe for "Basilico"*

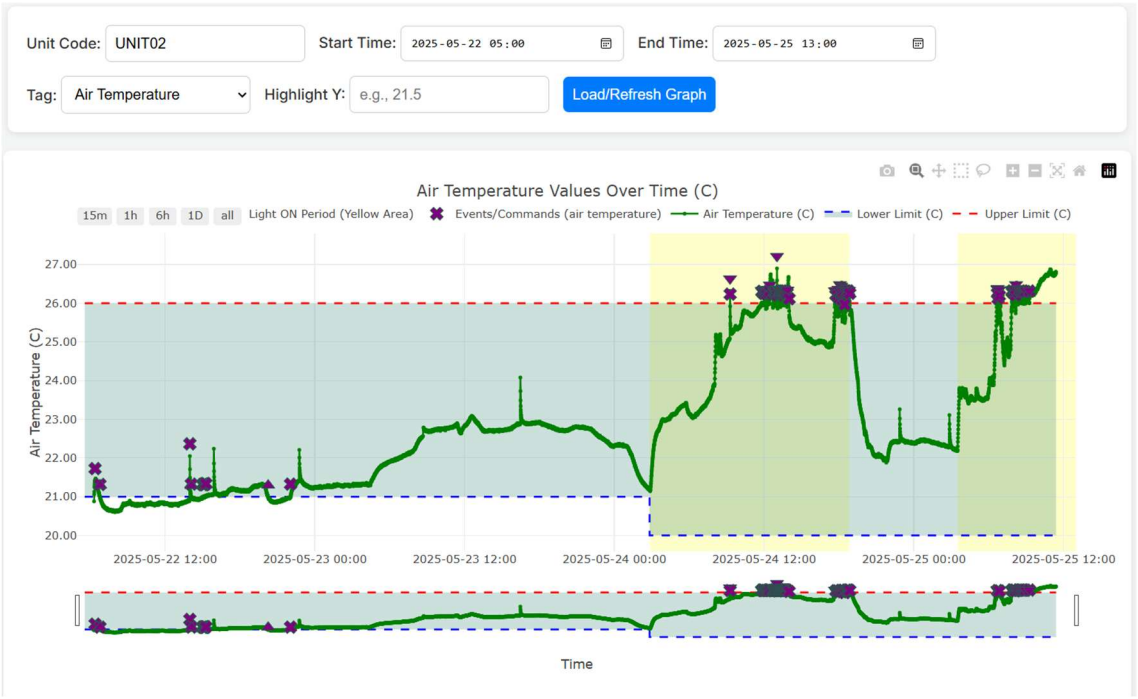



*Figure 58 Time-series plot of air temperature in Unit 02*




*Figure 59 Time-series plot of relative humidity in Unit 02*

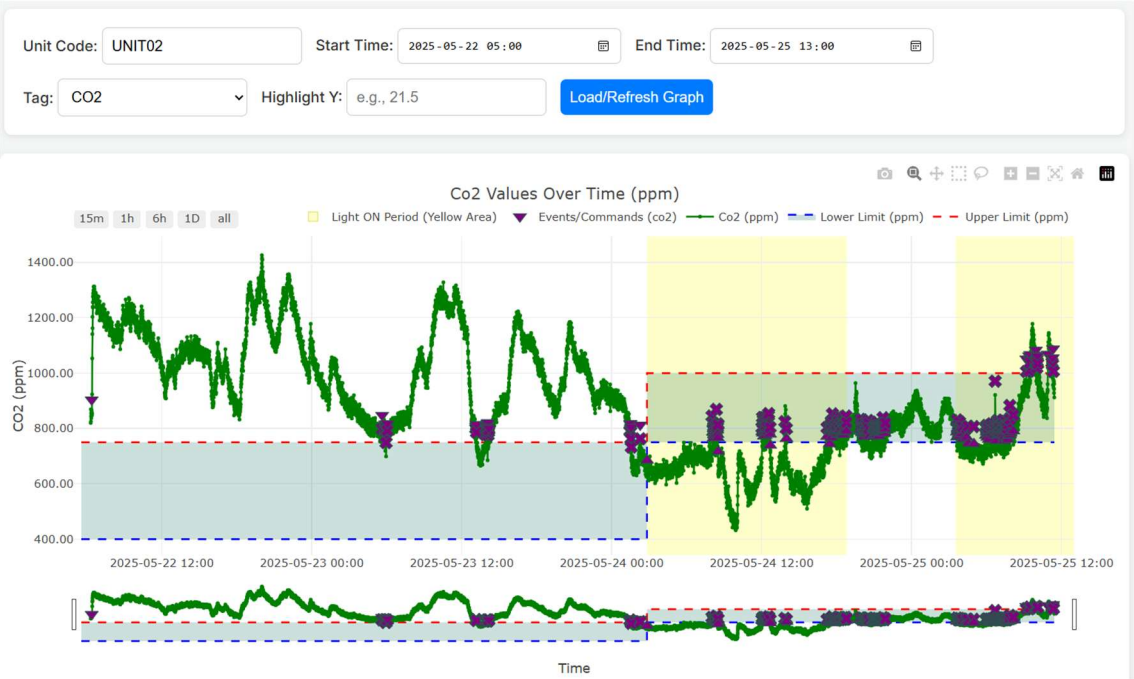



*Figure 60 Time-series plot of CO2 concentration in Unit 02*

The environmental control in Unit 02 for basil cultivation demonstrated a degree of stability comparable to Unit 01, with the system actively responding to maintain parameters within recipe limits. As shown in Figure 58 air temperature was generally maintained within the recipe's specified range (e.g., 21-26°C). The chart clearly shows the system activating Peltier cooling in response to deviations, particularly the temperature rise during light ON periods and time of the day.

Relative humidity, illustrated in Figure 59, was typically kept within the moderate range suitable for basil (e.g., targeting 70-90% during germination, then adjusting to 50-70% for vegetative growth). Maintaining precise humidity levels can be challenging due to plant transpiration rates and the efficiency of humidification or dehumidification systems, and Figure 59 reflects these dynamic interactions.

The lighting system successfully executed the programmed photoperiods, a critical factor for plant growth. Figure 60 shows that $CO_2$ enrichment from Unit 01, when active, led to an elevation of $CO_2$ levels in Unit 02, demonstrating the functional gas exchange (further detailed in Section 5.3). Any significant deviations from the basil recipe setpoints were often linked to external factors or the inherent limitations of specific actuators, such as the Peltier cooler's performance under high thermal load (discussed in Sections 5.4 5.5). Qualitative observations on basil indicated successful seed germination and

subsequent steady vegetative growth, including the development of true leaves, providing a positive context for the environmental conditions maintained by the system.

### 5.2.3 Discussion: Independent and Parallel System Operation

The collective results from sections 5.2.1 and 5.2.2, visually substantiated by the time-series data in Figure 55 to Figure 60, demonstrate the PFIoT prototype's core capability: managing two distinct cultivation environments simultaneously, with each unit independently adhering to its pre-programmed recipe. The charts clearly show different environmental setpoints (e.g., for temperature, humidity, CO2, and lighting schedules) being concurrently maintained in Unit 01 (mushrooms) and Unit 02 (basil). This occurred without direct interference between the units' primary environmental control loops, apart from the intentionally designed and controlled gas exchange mechanism.

The successful orchestration of these parallel operations is a direct outcome of the PFIoT platform architecture detailed in Chapter 4. Key architectural elements, such as the MQTT-based communication for sensor data telemetry and actuator commands, the Python-based run_recipe.py script for recipe execution, and the cea.run_agent() for control logic, were central to this achievement. The robust data model (Chapter 4 , Figure 26) played a crucial role by allowing clear segregation of unit-specific configurations, recipes, and sensor data. This enabled the Environment Control Agent to apply the correct, independent logic to each unit based on its specific recipe and real-time conditions.

This demonstrated success in parallel, independent recipe execution serves as a significant validation of the proposed PFIoT architecture's design principles, particularly its modularity and its potential for scalability in managing diverse and concurrent CEA operations.

## 5.3 CO2/O2 Exchange Between Cultivation Units

This section focuses on the results and implications of the implemented mechanism for exchanging CO2 produced in the fungal cultivation chamber (Unit 01) with the plant cultivation chamber (Unit 02), and potentially O2 in the reverse direction.

### 5.3.1 Implementation and Monitored Gas Exchange Dynamics

The $CO_2/O_2$ exchange was physically implemented using small fans and ducting connecting Unit 01 and Unit 02, with UVC sterilization in the airflow path to minimize cross-contamination, as detailed in the prototype setup (Chapter 4 , Figure 36). The control logic for activating the exchange fans was based on $CO_2$ levels in Unit 01 (e.g., initiating transfer when $CO_2$ exceeded a threshold suitable for plant enrichment) and/or timed schedules within the recipes.

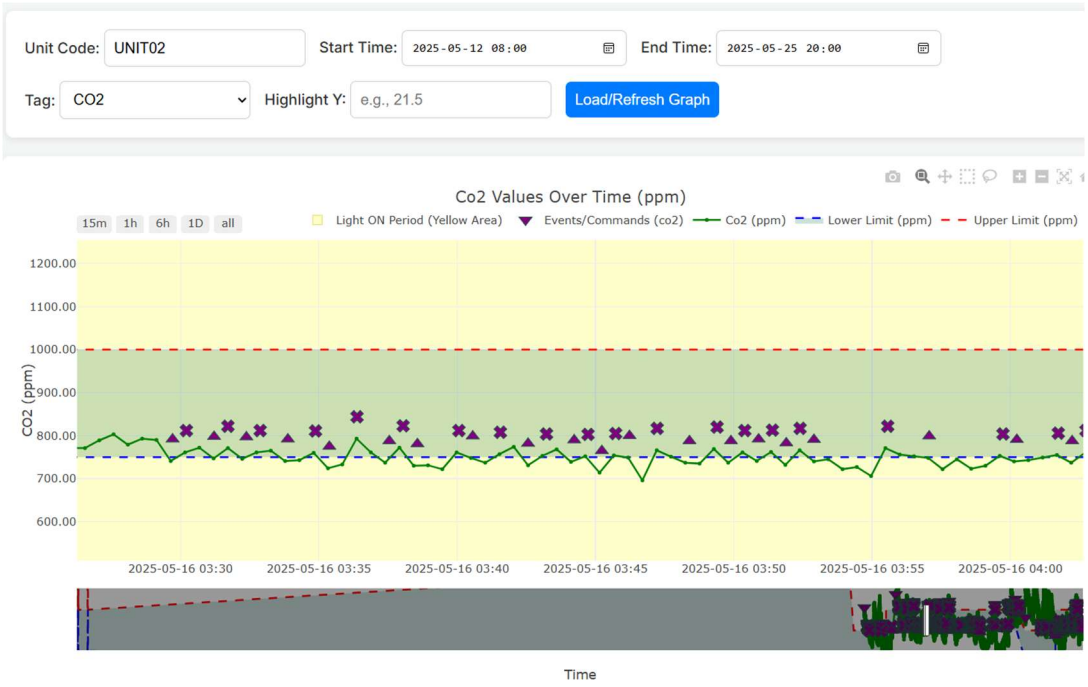



*Figure 61 CO2 provision to plant unit (UNIT2) from Mushroom unit (UNIT01)*

Figure 61 demonstrates the attempt of the Plant unit (UNIT02) to stabilise the CO2 concentration within the limits defined by the recipe by activating the air extraction from UNIT01 into UNIT02




*Figure 62 $O_2$ provision to mushroom unit (UNIT01) from plant unit (UNIT02)*

Figure 62 shows the system trying to increase the concentration of $O_2$ as referenced by the $CO_2$ concentration in the mushroom unit. The system consistently triggers commands to bring down the $CO_2$ concentration by activating the air flow from UNIT02 to UNIT01. We can see the cause-effect, still slow as UNIT02 at that time was still in the germination phase, thus $O_2$ production is low. Nevertheless, the system was able to control the setpoint by renovating the chamber air.

### 5.3.2 Effectiveness and Implications of Gas Exchange

The results (as depicted in Figure 61 and Figure 62, indicate that the gas exchange system was effective in transferring $CO_2$-enriched air from the fungal cultivation unit (UNIT01) to the plant cultivation unit (UNIT02), and vice-versa for $O_2$-rich air (though $O_2$ impact is less pronounced). The observed elevation of $CO_2$ levels in UNIT02 during exchange periods (Figure 61) suggests a successful implementation of this resource-sharing concept. The potential benefits of this exchange include providing supplementary $CO_2$ for basil in UNIT02, which, as discussed in subsection 2.2.1 can enhance photosynthetic rates and potentially improve plant growth and yield, especially in a sealed or semi-sealed environment where $CO_2$ might otherwise become depleted. For the mushroom unit, venting $CO_2$ (either to the plant unit or externally) is crucial during certain developmental stages (e.g., pinning and fruiting) to trigger and support proper

mushroom formation. The attempt to use $O_2$ from the plant unit (Figure 62) shows the system's capability, though its effectiveness is limited by the plants' $O_2$ production rate at early stages.

Challenges and limitations encountered during the gas exchange process might include:

- **Balancing airflow**: Ensuring sufficient airflow to achieve meaningful gas transfer without creating excessive drafts or temperature disturbances in either chamber. The small fans used might have limited capacity for rapid or large-volume exchange.
- **Preventing contamination**: While UVC sterilization was implemented, the risk of airborne microbial or spore cross-contamination between the units, though minimized, cannot be entirely eliminated without more sophisticated filtration.
- **Efficiency of transfer**: The actual amount of $CO_2$ effectively utilized by the plants versus lost through chamber leakage would be difficult to quantify precisely without more detailed gas analysis. The airtightness of the chambers (as mentioned in Chapter 2.1 for PFALs) would be a critical factor here.
- **Oxygen transfer effectiveness**: Demonstrating significant $O_2$ transfer from the plant to the fungal unit was less evident in Figure 62, as $O_2$ production by small plant seedlings is relatively low, and fungal $O_2$ requirements are generally met by ambient air unless the chamber is extremely airtight and densely packed.

This practical demonstration of inter-unit gas exchange supports the symbiotic relationship concept discussed in Chapter 2.2.3 and the integrated system design in Chapter 3.2.3. It highlights a tangible way to improve resource circularity within a multi-crop CEA facility, potentially reducing the need for external $CO_2$ supplies for plant enrichment and managing $CO_2$ buildup in fungal cultivation.

## 5.4 Actuator Performance and Limitations: Peltier Cooling

This section addresses the specific performance observations and identifies limitations of the Peltier thermoelectric cooler (TEC) units employed for temperature reduction in the prototype chambers.

Peltier coolers (12V 120W, as per Chapter 4 Figure 52) were installed in both Units to provide active cooling when chamber temperatures exceeded the upper setpoint defined by the active recipe.

The effectiveness of the Peltier coolers in achieving and maintaining target temperatures was found to be moderate under low to medium heat loads but limited under high ambient temperatures or significant internal heat. Quantification of their cooling capacity based on observations from Figure 58 might indicate, for example, the Peltier unit in Unit 02, when activated during light ON periods, often struggled to reduce the internal chamber temperature more than 1-2°C below the point it would have reached without cooling, frequently operating near the 26°C upper limit and below what it would have been without active cooling, but rarely achieved the lower end of the target range during high load periods.

**Limitations of Peltier Actuators:**

The primary limitations observed with the Peltier cooling system, evident from its performance in charts like Figure 58, included:

- **Insufficient cooling power:** For the given chamber volume (approx. 45L) and potential heat loads (e.g., from ambient conditions, LED lights), the 120W Peltier unit often struggled to achieve significant temperature reductions, especially if the target temperature was substantially below the ambient or if internal heat generation was high. This is evident in Figure 58 where the temperature in Unit 02 frequently "hugs" the upper 26°C limit during light ON periods, despite cooler activation.
- **Slow response time:** The rate of temperature decrease was often slow, meaning it took a considerable amount of time for the Peltier unit to bring the chamber temperature down to the desired setpoint after a heat-inducing event or if the temperature drifted upwards. This can be inferred from the prolonged periods at the upper boundary in Figure 58.
- **High energy consumption for effect:** Peltier devices are known for their relatively low coefficient of performance (COP) compared to vapor-compression refrigeration. While not explicitly measured in detail but observed

that the coolers ran for extended periods to achieve modest cooling, implying significant energy use for the cooling effect delivered.

- **Sensitivity to ambient temperature and heat dissipation**: The cooling capacity of a Peltier device is highly dependent on the temperature differential it operates against and the efficiency of heat dissipation from its hot side. If the hot-side heatsink and fan were not optimally efficient or if the ambient air used for dissipation was already warm, the cooling performance on the cold side was noticeably diminished.

**These limitations are likely due to a combination of factors:**

- Potentially undersized units: A single 120W Peltier might be at the lower end of adequacy for actively cooling a 45L chamber with internal heat sources and imperfect insulation, especially if aiming for significant temperature drops.
- **Inherent efficiency of Peltier technology:** TECs are generally less efficient than traditional cooling methods for larger cooling loads.
- **Heat dissipation challenges:** The effectiveness of the hot-side heatsink and fan in a confined prototype setup could have limited overall performance. Inadequate removal of heat from the hot side directly reduces the cold side's ability to cool.

These limitations directly impacted the system's ability to consistently maintain optimal low temperatures, especially in Unit 02 (plants) if grow lights generated substantial heat, or if attempting to run recipes requiring temperatures significantly below ambient. This could lead to periods where the temperature hovered at the upper boundary of the recipe's tolerance. For scalability to larger CEA systems, relying solely on Peltier cooling of this type would likely be impractical and economically unviable due to the sheer number of units required, the cumulative energy consumption, and the challenges in managing heat dissipation from many hot sides. More conventional cooling technologies (e.g., small heat pumps, air conditioning) would be necessary for larger volumes.

## 5.5 Analysis of Rule-Based Control Under External Disturbances

This section presents and discusses the performance of the implemented rule-based control system, particularly its behaviour when the cultivation chambers were subjected

to external environmental influences or disturbances. The prototype's location in an environment subject to daily weather patterns and ambient temperature fluctuations provides a realistic testbed for observing these interactions.

### 5.5.1 System Response to Externalities

During the operational trials, the prototype system was exposed to several types of external disturbances common in a non-laboratory setting, as the trials were run in a home office environment. These included:

- Fluctuations in the ambient room temperature where the prototype was located (e.g., day/night variations, changes due to building HVAC).
- Heat generated by auxiliary equipment operating within or near the chambers (e.g., power supplies, LED grow lights in Unit 02).
- Brief disturbances caused by opening chamber doors for manual operations, substrate introduction, or qualitative observation of the crops.

The system's response to these externalities is clearly illustrated in the air temperature monitoring charts for both cultivation units.

- Unit 02 (Basil - Plant Chamber, Figure 58): During periods when the LED grow lights are active (indicated by the yellow "Light ON Period" background), a significant internal heat load is introduced. As seen around 2025-05-24 12:00 and subsequently, the air temperature in Unit 02 (green line) consistently rises, frequently approaching or reaching the upper boundary limit of 26°C defined by the "Basilico" recipe. The numerous "Events/Commands" (purple marks, indicating Peltier cooler activation with "DOWN" commands) during these light periods demonstrate the rule-based control system actively attempting to counteract this heat. However, the temperature often "hugs" this upper limit, indicating that the cooling actuator, under the load of both internal heat from LEDs and potentially higher daytime ambient temperatures, struggles to maintain a significant margin below the threshold. The cyclical nature of the lights (tied to the time of day) directly imposes a recurring thermal challenge.
- Unit 01 (Oyster Mushroom Chamber, Figure 55): While Unit 01 does not have the intense internal heat load from grow lights seen in Unit 02, its temperature profile also demonstrates the system's continuous effort to maintain stability. The

chart (particularly the longer view from 2025-05-22 to 2025-05-25) shows the air temperature (green line) fluctuating around the setpoint boundaries (e.g., 20-25°C, then adjusted to 18-20°C). The frequent "Events/Commands" (purple marks) indicate that the heating or cooling elements are regularly activated. These fluctuations, even during periods without internal light-generated heat, suggest the influence of external ambient conditions. For instance, slight but persistent drifts towards the lower or upper limits, requiring corrective action, can be attributed to the time-of-day changes in room temperature due to external weather, as the prototype is not in a perfectly insulated laboratory environment. The system is constantly working against these subtle, weather-influenced ambient temperature shifts. Figure 63 further illustrates this active management, showing the temperature oscillating closely around the lower setpoint (approx. 20°C) with frequent control interventions.

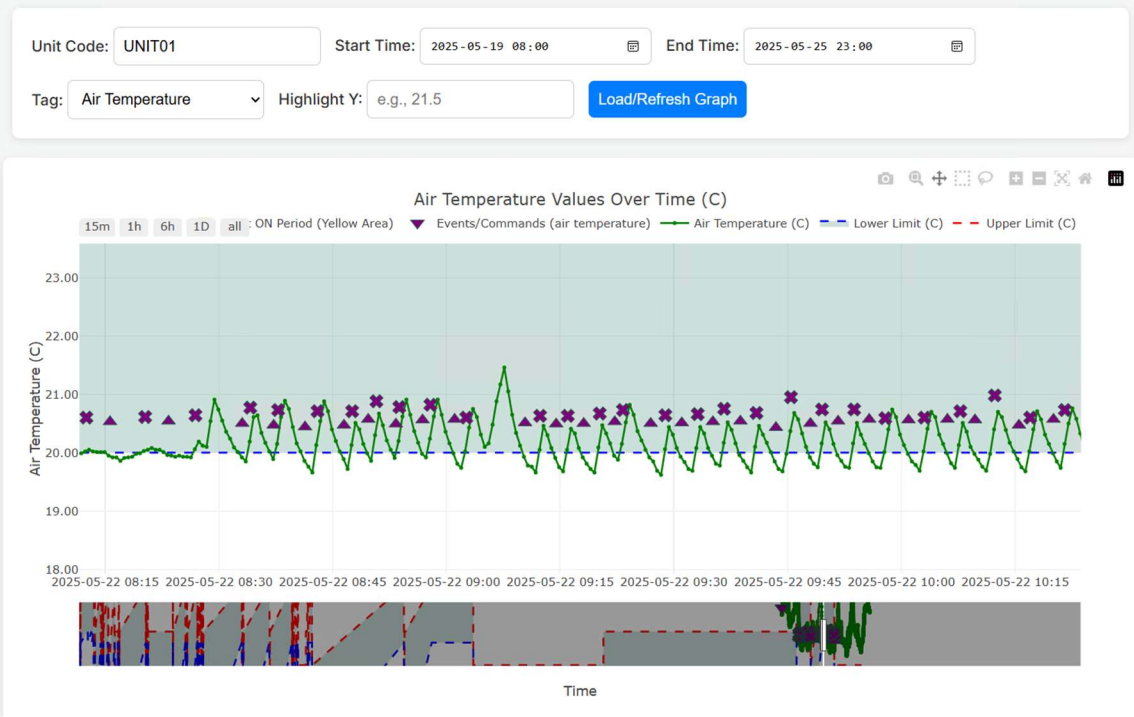



*Figure 63 Temperature control in Unit01.*

### Discussion of System Response

The rule-based control system, as implemented by the *cea.run_agent()* logic (Chapter 4 ), responded to these disturbances by activating the relevant actuators (heater, Peltier cooler) once a sensor reading crossed a predefined setpoint threshold.

As demonstrated in Figure 58 (Unit 02), the heat from the grow lights (an internal externality tied to a daily schedule) combined with the ambient room temperature (influenced by external weather and time of day) caused the air temperature to frequently challenge the upper limit of the basil recipe. The control system commanded the Peltier cooler to activate, but its limited capacity under the combined thermal load meant the temperature often stabilized at or close to this 26°C boundary. This illustrates the system working at its operational edge due to these combined internal and external pressures.

Similarly, in Figure 55 (Unit 01), while the temperature control appears more stable within the wider deadband of the mushroom recipe, the persistent small corrections suggest the heating pad or cooler is frequently engaged to counteract ambient temperature drifts. These drifts are likely influenced by the daily cycle of external temperatures affecting the room where the prototype is housed, demonstrating the system's susceptibility to weather-related externalities. The control system is reactive, addressing these deviations as they push the internal temperature towards the recipe limits.

Limitations of Rule-Based Control

The observed behaviour, where the system's environmental parameters often operate at or very near the defined boundary limits, especially when under stress from external or internal disturbances, is a characteristic outcome of the implemented simple, threshold-based rule-based control.

This "boundary-hugging" behaviour occurs because the control logic (e.g., IF temperature > upper setpoint THEN cool ON; IF temperature < lower setpoint THEN heat ON) is purely reactive. It only initiates corrective action after a boundary has been approached or crossed.

#### *5.5.1.1 Evidence from Figure 58 (Unit 02)*

When the LED lights turn on, the temperature climbs. The Peltier cooler is activated (purple marks for "DOWN" commands appear) only as the temperature nears or hits the 26°C upper limit. The cooler then runs, often continuously, struggling to bring the temperature significantly lower, effectively pinning it to the boundary. This shows the system reacting to, not anticipating, the heat load.

#### 5.5.1.2 Evidence from Figure 55 (Unit 01)

The temperature trace shows oscillations around the setpoints. For example, around 2025-05-22 09:00, the temperature dips towards the lower limit, triggering heating commands, then overshoots slightly, potentially requiring cooling, illustrating a reactive cycle. The system lacks the sophistication to anticipate trends (e.g., predict that the ambient temperature will continue to drop at night) or modulate actuator output proportionally to the error or the rate of change of the disturbance. When a strong external force (like sustained heat from LEDs or a persistent cold ambient condition due to time of day/weather) pushes a variable towards a limit, the actuator (especially if its capacity is limited, like the Peltier cooler) might only be able to counteract that force at the boundary, leading to prolonged operation there.

#### 5.5.1.3 Inherent limitations

Inherent limitations of this type of control, as evidenced by the charts:

- **Reactive rather than proactive or predictive:** The charts consistently show control commands being issued in response to the actual temperature nearing or crossing a limit. The system waits for the deviation before acting. For example, it does not pre-emptively start cooling in Unit 02 just before the lights, a known heat-generating event tied to the time of day, are scheduled to turn on.
- **Potential for oscillations or "hunting":** Figure 55, over its extended duration, shows the temperature oscillating around the setpoints, particularly visible when the recipe setpoints change (e.g., around 2025-05-23 00:00). This indicates the system correcting, potentially overshooting, and then correcting again, a common trait if the deadband (hysteresis) is not perfectly tuned or if actuators have a simple on/off nature.
- **Difficulty in achieving fine-tuned, stable control within a narrow band:** Both Figure 55 and Figure 58 clearly demonstrate this. The temperature lines frequently touch or "ride" the upper or lower boundaries for extended periods, rather than maintaining a stable position in the middle of the desired range. This is particularly evident in Figure 58 during the light-on periods. The system is constantly fighting to push the temperature back from a boundary, only for the external/internal load to push it back again.

- **Lack of adaptive capability:** The control rules are fixed. The system cannot learn from past performance or adapt its response if the baseline conditions change (e.g., if the average ambient room temperature is significantly different between a cold night and a warm day due to weather). The charts show it applying the same threshold-based logic regardless of the underlying baseline thermal load, leading to more pronounced boundary-hugging when external conditions are more challenging.

As discussed in the literature review (Chapter 2.3 on Control Theory and Chapter 3.1.1 on Platform Tier capabilities like ML Control Law), more advanced control strategies such as PID (Proportional-Integral-Derivative) control, MPC (Model Predictive Control), or ML-based approaches offer potential solutions. PID controllers, for example, adjust actuator output based on the current error, the accumulated error, and the rate of change of error, allowing for smoother and more precise control. MPC can optimize control actions over a future horizon by using a model of the system. These advanced methods could potentially mitigate the boundary-hugging behaviour observed in Figure 55 and Figure 58 by providing more nuanced and anticipatory responses to both scheduled internal loads (like lights) and fluctuating external ambient conditions.

**Importance of Robust Control:** This observed behaviour, clearly depicted in the operational charts, underscores the importance of robust and sophisticated control systems for maintaining truly optimal and stable environmental conditions in CEA. This is especially critical when systems are deployed in environments subject to dynamic external factors like daily weather patterns and ambient temperature shifts, or significant internal loads like lighting. Operating consistently at the edge of tolerance limits, as seen in the charts, can stress the cultivated organisms, potentially impact growth or quality, and lead to inefficient energy use by actuators.

## 5.6 Overall Discussion

The operational evaluation of the PFIoT prototype successfully demonstrated its core design objectives. The system capably managed two distinct cultivation units (Unit 01 for *Pleurotus ostreatus* and Unit 02 for *Ocimum basilicum*) in parallel, each adhering to its independent environmental recipe, as evidenced by the data presented in Figure 55 - Figure 60. Furthermore, the prototype realized a functional inter-unit gas exchange

mechanism, allowing for the transfer of $CO_2$ from the fungal chamber to the plant chamber (Figure 61) and a reciprocal attempt for $O_2$ (Figure 62), showcasing a practical application of resource circularity.

**Summary of Achievements and Limitations:**

- **Achievements:**
    - Successful implementation of a multi-unit control architecture based on the proposed PFIoT reference model.
    - Demonstrated independent recipe execution for diverse organisms (fungi and plants).
    - Functional CO2 exchange between units, validating a key aspect of integrated, symbiotic cultivation.
    - Effective data logging and traceability of sensor readings, control commands, and actuator setpoints via the MQTT broker and database persistence (as detailed in Chapter 4 and foundational to the presented charts).
- **Limitations:**
    - The Peltier thermoelectric coolers exhibited limited cooling capacity and slow response times, particularly under significant thermal loads or higher ambient temperatures, constraining the system's ability to achieve and maintain lower target temperatures effectively (evident in Figure 58).
    - The implemented rule-based control strategy, while functional, showed limitations when subjected to external environmental disturbances, often resulting in system parameters operating at the defined boundary limits of the recipes rather than maintaining a stable midpoint (discussed in detail in Section 5.5, with evidence from Figure 55 and Figure 58).

These findings provide valuable insights into the practical implementation of the PFIoT architecture (Chapter 1.4). The successful parallel operation and gas exchange confirm the viability of the modular, message-driven design. However, the observed limitations highlight critical areas for improvement, particularly in actuator selection for thermal management and the sophistication of the control algorithms. The results contribute to the understanding of designing PFIoT architectures by underscoring the need for careful consideration of actuator capabilities matched to environmental loads

and the necessity of control strategies that can robustly handle real-world variability beyond simple thresholding.

**Connection to Literature:**

- The system's performance in managing parallel units aligns with the objectives of flexible and modular CEA systems discussed in the literature (e.g., [21][15] [18] regarding standardization and multi-vendor systems, though this prototype is single-developer). The successful $CO_2$ exchange provides a practical, albeit small-scale, demonstration of the symbiotic cultivation concepts reviewed (Chapter 2.2.3, [139]).
- The identified limitations regarding Peltier cooling are consistent with known characteristics of thermoelectric devices when applied to non-trivial cooling loads. The challenges with rule-based control under disturbance echo the broader discussion in control theory (Chapter 2.3) that favours more adaptive and predictive control methods for complex, dynamic systems [93].
- While the prototype did not implement advanced ML control, the results from the rule-based system provide a baseline that motivates the future integration of such advanced techniques, as conceptualized in the PFIoT architecture (Chapter 3 , Figure 14).

**Addressing the "Boundary Limits" Issue**

The consistent operation of the system at the boundary limits of control parameters under external stress is significant. This state indicates that the system is struggling to maintain the desired environment and is essentially at the edge of its control capability with the current actuators and logic. Such operation can lead to:

- **Suboptimal conditions for crops**: While within tolerance, conditions at the extreme edges of a recipe may not be optimal for growth, quality, or specific metabolic processes.
- **Increased energy consumption:** Actuators (like heaters or coolers) running continuously or cycling rapidly at their maximum capacity to fight disturbances are inherently less energy efficient.

- **Reduced lifespan of components:** Constant, high-demand operation can accelerate wear and tear on actuators and other system components. This observation strongly suggests that for robust and efficient CEA, particularly for commercial-scale applications, the control system must be designed with sufficient headroom in actuator capacity and employ control algorithms that can maintain stability well within the desired parameter ranges, not just at their periphery.

## 5.7 Summary

This chapter presented the experimental results from the operational evaluation of the PFIoT prototype. Key findings demonstrated the system's successful capability to manage two independent cultivation units (*Pleurotus ostreatus* and *Ocimum basilicum*) in parallel, each following distinct environmental recipes. The functional interchange of $CO_2$ between these units was also successfully demonstrated, supporting concepts of resource circularity.

The main points of discussion highlighted the strengths of the modular architecture in achieving these parallel operations. However, significant limitations were identified concerning the cooling performance of the Peltier actuators under realistic thermal loads and the tendency of the rule-based control system to operate at the boundary limits of setpoint ranges when faced with external environmental disturbances. These limitations underscore the need for careful actuator selection and more sophisticated control strategies for robust CEA operations.

The findings and discussions presented herein provide a foundation for the final conclusions of this thesis and inform recommendations for future research and system development, which will be elaborated upon in Chapter 6 .

# Chapter 6 Conclusions and Future Work

## 6.1 Recapitulation of the Purpose and Objectives of the Research

This thesis addressed the growing challenge of global food security, exacerbated by factors such as climate change, depletion of natural resources, pollution, population growth, and changes in consumption patterns. These elements create a scenario of uncertainty for the future of food production and the sustainability of current agricultural systems, which are incompatible with the need for increased production for a global population projected grow. In this context, Controlled Environment Agriculture (CEA) and, more specifically, Plant Factories (PF), emerge as promising solutions, allowing crop production in closed environments with full control over production factors.

However, despite their potential, PFs face significant obstacles that hinder their widespread adoption, namely the high installation and operational costs, with particular emphasis on energy consumption, and the lack of standardization in their technological platforms and Internet of Things (IoT) implementations. This technological heterogeneity results in difficulties in system integration, limits interoperability, increases investment risks, and hinders the development of scalable and economically efficient solutions. The need for optimized, standardized, and robust digital infrastructures is, therefore, pressing to unlock the full potential of PFs.

The central motivation for this research lay in the conviction that digital technologies, particularly those associated with the Industrial Internet of Things (IIoT) and Industrie 4.0 concepts, can offer solutions to these challenges. The transfer of knowledge and technology from more mature industrial sectors, such as manufacturing, which have already undergone digital transformations, was seen as a promising avenue.

Within this framework, the main research question that guided this thesis was:

***How can an open, standardized, and cost-efficient IoT reference architecture be designed and prototyped to effectively monitor and control the environment in a digital plant factory, potentially integrating diverse cultivation types like plants and fungi?***

To answer this question, the following specific objectives were established:

1. Conduct a review of the state-of-the-art in Plant Factories, including their challenges, the environmental factors influencing crop growth (plants and fungi), biological responses, control systems, and relevant IIoT technologies and reference architectures.
2. Propose a standardized PFIoT (Plant Factory Internet of Things) reference architecture, based on established IIoT principles and reference models (such as RAMI 4.0 and IIRA), adapted to the specific needs of Plant Factories.
3. Design and implement a small-scale functional prototype that demonstrates the core capabilities of the proposed PFIoT architecture, focusing specifically on the integration and control of separate cultivation chambers for plants and fungi with automated gas exchange.
4. Evaluate the performance of the developed prototype in terms of its ability to monitor environmental conditions, execute control commands, maintain setpoints, and manage the integrated system.

The research thus sought to contribute to making PFs more viable, scalable, and accessible by proposing a PFIoT platform that serves as a basis for automating environmental control, optimizing resource use, and enabling data-driven decision-making, with the potential to support more versatile cultivation systems.

## 6.2 Summary of Key Findings and Contributions

To achieve the outlined objectives, the research developed and evaluated a PFIoT reference architecture and a functional prototype. The main findings and contributions are summarized below.

### 6.2.1 Proposed PFIoT Architecture

A three-tier PFIoT reference architecture (Edge, Platform, and Enterprise) was proposed, detailed in Chapter 3 . This architecture was designed based on established IIoT principles, such as the RAMI 4.0 and IIRA models, aiming for standardization, modularity, and the ability to integrate diverse cultivation types, namely plants and fungi. The Edge layer is responsible for real-time interaction with physical assets (sensors and actuators). The Platform layer acts as the "brain" of the system, responsible for data processing, analysis, storage, and orchestration of control logic, including the potential

implementation of Machine Learning Control Law (ML Control Law). The Enterprise layer is intended for business applications and decision support systems. This structure aims to address the heterogeneity and lack of standards identified as challenges in the PF industry.

### 6.2.2 Prototype Implementation and Evaluation

A small-scale prototype was implemented (Chapter 4 ) and evaluated (Chapter 5 ) to validate the architectural concepts. The main findings from the experimental evaluation include:

- **Parallel Operation of Independent Cultivation Units:** The system successfully demonstrated the ability to simultaneously manage two distinct cultivation units: Unit 01, dedicated to the cultivation of *Pleurotus ostreatus* (Oyster Mushroom), and Unit 02, for the cultivation of *Ocimum basilicum* (Basil). Each unit operated according to its specific pre-defined environmental recipe, with the system maintaining parameters such as temperature, humidity, and $CO_2$ concentration within defined limits, albeit with some limitations. This parallel and independent management capability validates the modularity and scalability potential of the PFIoT architecture for diversified and concurrent CEA operations.
- **$CO_2$/$O_2$Exchange Between Cultivation Units:** The prototype successfully implemented a mechanism for exchanging atmospheric gases between the two units. Controlled transfer of $CO_2$-enriched air from the fungal cultivation unit (Unit 01) to the plant cultivation unit (Unit 02) was demonstrated, along with an attempt to transfer $O_2$ in the reverse direction. This functionality validates the concept of symbiotic resource utilization and represents a practical step towards resource circularity in PFs, aligning with discussions on symbiotic relationships and integrated system design.
- **Actuator Performance (Peltier Coolers):** The evaluation revealed significant limitations in the performance of the thermoelectric Peltier coolers (120W) used for temperature control. Their effectiveness was moderate under low to medium thermal loads but considerably limited under high ambient temperatures or significant internal heat generation (e.g., from LED lighting). Insufficient cooling capacity for the chamber volume, slow response times, and an apparent high

energy consumption for the cooling effect obtained were observed, often leading to the temperature operating at the upper limit of the recipe.

- **Performance of Rule-Based Control:** The implemented rule-based control system, while functional in generally maintaining parameters, demonstrated a reactive nature. Faced with internal (e.g., heat from LED lights) or external (e.g., fluctuations in ambient temperature) disturbances, environmental parameters frequently operated at the limits defined by the recipes, a behaviour described as "boundary-hugging". This characteristic indicates that the system only initiated corrective actions after approaching or crossing a limit, without the ability to anticipate trends or proportionally modulate actuator output.

### 6.2.3 Main Contributions of the Thesis

Based on the findings, the main contributions of this thesis are:

1. **An adaptable PFIoT reference architecture:** Specifically designed for PFs, addressing the needs for standardization, modularity, and integration of different cultivation types, and grounded in recognized IIoT models.
2. **A small-scale functional prototype:** Which validated the core architectural concepts, including the challenging integration of plant and fungal cultivation with automated gas exchange, demonstrating the feasibility of information management and multiple unit management.
3. **Empirical knowledge on the performance and limitations:** Of specific low-cost hardware components (such as Peltier coolers) and basic control strategies (rule-based) in a PF context, providing practical data on their operational challenges.
4. **An operational framework and a foundational dataset:** That serve as a basis for future research into more advanced control systems and PF optimization, especially concerning environmental stability and energy efficiency.

The distinction between the architecture's success in managing information flow and multiple units, and the performance limitations of the physical components and simple control logic, is fundamental. The proposed architecture functions as a robust blueprint,

but its full realization in terms of efficiency and optimal control requires more sophisticated "building materials" (actuators, control algorithms).

## 6.3 Answers to Research Questions

This section directly addresses the main research question and the specific objectives that guided this work.

**Answer to the Main Research Question**

The central question of the thesis was:

***How can an open, standardized, and cost-efficient IoT reference architecture be designed and prototyped to effectively monitor and control the environment in a digital plant factory, potentially integrating diverse cultivation types like plants and fungi?***

This research demonstrated that such an architecture can be designed by adapting principles and reference models from IIoT (RAMI 4.0, IIRA) to the specific domain of PFs, resulting in a three-tier structure (Edge, Platform, Enterprise) that promotes openness and standardization (Chapter 3 ). The developed prototype (Chapter 4 ) validated the feasibility of this architecture for basic environmental monitoring and control, as well as for integrating plant and fungal cultivation units with automated gas exchange, an innovative aspect of the system.

Regarding "cost-efficiency" and "effective control," the answer is more limited. The proposed architecture establishes a *framework* for cost-efficiency through the potential use of open-source components and standardization, which can reduce development and integration costs. However, the *operational* cost-efficiency and "effective control" of the prototype were partially achieved due to the identified limitations in the chosen low-cost components (e.g., energy consumption and cooling capacity of Peltier coolers) and the simplicity of the rule-based control logic, which resulted in suboptimal performance under dynamic disturbances. Thus, while the *design* and *prototyping* of an architecture with the desired characteristics were achieved, the full realization of cost-efficiency and robust, effective control requires the incorporation of more suitable components and more advanced control algorithms within the proposed architecture.

**Answers to Specific Objectives**

1. **Conduct a review of the state-of-the-art:** A comprehensive literature review was conducted (Chapter 2 ), covering PF concepts, biological requirements of plants and fungi, control theory, relevant IIoT technologies, and reference architectures, identifying research gaps and informing the development of the proposal.
2. **Propose a standardized PFIoT reference architecture:** A three-tier PFIoT architecture was proposed and detailed (Chapter 3 ), explaining its components, functionalities, and design rationale, including considerations for integrating plant and fungal cultivation.
3. **Design and implement a small-scale functional prototype:** A prototype was successfully designed and implemented (Chapter 4 ), demonstrating the core capabilities of the PFIoT architecture, including the monitoring and control of two interconnected chambers (one for plants, one for fungi) with automated gas exchange.
4. **Evaluate the performance of the developed prototype:** The prototype was evaluated (Chapter 5 ), generating knowledge about its performance in monitoring environmental conditions, executing control commands, maintaining setpoints, and managing the integrated system, including the identification of important limitations.

In summary, the thesis answered the main research question by presenting an architectural design and a functional prototype that meet the requirements of openness, standardization, and integration. The aspects of "cost-efficient" and "effective control" were addressed conceptually in the architecture, but their practical implementation in the prototype revealed areas needing future development to achieve optimal and robust performance.

## 6.4 Implications of the Research

The results and contributions of this thesis have significant practical and theoretical implications for the field of Plant Factories and Controlled Environment Agriculture.

### Practical Implications

The proposed PFIoT architecture can serve as a model or blueprint for developing more standardized and interoperable digital platforms in the PF industry. By basing itself on established IIoT models like RAMI 4.0 and IIRA, the architecture promotes a structured approach that can facilitate the integration of components from different vendors, potentially reducing development costs, investment risks, and integration complexities for new operators or those seeking to modernize existing facilities. The lack of standardization is one of the main obstacles to the widespread adoption of PFs, and this proposal contributes to mitigating this problem.

The successful demonstration of integrated plant and fungal cultivation with $CO_2$/$O_2$ exchange (Chapter 5.3) offers a practical pathway to increase resource circularity and sustainability in PFs. This approach can reduce operational costs, for example, by decreasing the need for external $CO_2$ supplementation for plants and improve the environmental profile of CEA by reusing metabolic byproducts.

### Theoretical Implications

This research contributes to the body of knowledge on applying IIoT principles to the specific domain of agriculture, particularly PFs. It demonstrates the transferability of generic industrial architecture models to biological production systems but also highlights the unique adaptations needed to handle the complexity and dynamism of living organisms and their controlled environments. The way the PFIoT architecture maps RAMI 4.0 and IIRA concepts to the needs of PFs (Chapter 3 ) constitutes a contribution to systems engineering in this domain.

The findings on the performance and limitations of specific actuators (Peltier coolers) and simple control strategies (rule-based) in a small-scale, low-cost system provide valuable empirical data. This data can inform more sophisticated modelling and simulation efforts for environmental control in PFs, helping to predict system behaviour

under different hardware and software configurations. The feedback obtained from the practical application of theory (the architecture) to a specific implementation (the prototype), and the subsequent observations on challenges at the physical level (actuators, control stability), refine the understanding of how these technologies interact in the real world. It becomes evident that while high-level IIoT architectures are adaptable, the final interface with biological systems and the physical environment – the "last mile" – requires domain-specific optimization and careful component selection.

Additionally, the thesis underscores the importance of considering the PF system as a complex cyber-physical system, where interactions between digital control components and physical biological and environmental processes are intrinsically linked and dynamic. The need for closed feedback loops and control strategies that can handle uncertainties and disturbances is a central theme emerging from the theoretical analysis and experimental results.

## 6.5 Limitations of the Research

Despite the contributions and findings presented, this research has inherent limitations that must be acknowledged to properly contextualize the results and guide future work. These limitations were identified in the scope and delineation of the thesis (Chapter 1.5) and were corroborated or further detailed by the experimental results (Chapter 5 ).

- **Scale and Representativeness:** The developed prototype is small-scale and not representative of a commercial Plant Factory. Although the architectural principles were validated, challenges related to managing larger thermal loads, more complex workflows, or the logistics of a commercial operation remain unaddressed in this specific implementation. Direct scalability to commercial PFs would require additional engineering and component upgrades.
- **Component Selection:** Low-cost hardware components (e.g., ESP32, Peltier coolers, specific sensors) and open-source software were used. The performance of these components, notably the limited cooling capacity of the Peltier coolers and their apparent low energy efficiency, may not reflect that of industrial-grade solutions, which would typically be more robust and expensive.
- **Experimental Duration:** The experimental evaluation period was limited. This time constraint prevented a long-term stability analysis of the system or the

evaluation of complete cultivation cycles for the tested species. Consequently, conclusions about sustained performance and long-term biological results are preliminary.

- **Cultivation Complexity:** Active control in the prototype was limited to basic environmental parameters such as air temperature, humidity, and $CO_2$. Crucial aspects like nutrient delivery were manual, and light control was restricted to photoperiod management, without dynamic adjustments of spectrum or intensity. The assessment of plant and fungal growth was qualitative, lacking detailed quantitative measurements of yield or quality.
- **Economic Analysis:** A detailed cost-benefit analysis or a life cycle assessment of the proposed architecture or prototype was not part of the scope of this thesis. Therefore, the research does not provide definitive conclusions about the financial viability or environmental impact of implementing such a system on a larger scale.
- **Simplicity of the Control Algorithm:** Although the PFIoT architecture conceptualizes the use of advanced Machine Learning (ML) or Artificial Intelligence (AI) based control, the prototype implemented only simple, rule-based control strategies. These demonstrated limitations, such as "boundary-hugging" behaviour and the inability to proactively respond to disturbances. This is an important limitation regarding the claim of "effective control" under dynamic conditions.
- **Specific Actuator Performance:** Beyond the general limitations of component selection, the insufficient performance of the Peltier coolers in maintaining stable temperatures under thermal load was a specific and significant limitation that impacted the system's ability to strictly follow cultivation recipes under all conditions.

These limitations do not invalidate the findings but define the boundaries of the current study. They serve as crucial starting points for the "Recommendations for Future Work" section, clearly outlining areas where additional research and development are needed to bring the PFIoT architecture and similar systems closer to a robust and commercially viable solution.

## 6.6 Recommendations for Future Work

Based on the findings, contributions, and limitations identified in this thesis, the following directions for future research and development in the field of Digital Plant Factories are proposed:

### Improvement of Control Systems

The most evident limitation of the prototype was the performance of the rule-based control system, which proved reactive and prone to operating at recipe limits under disturbance. The theoretical discussion (Chapter 2.3) and the conceptualization of the PFIoT architecture (Chapter 3.1.1) already pointed to the need for more advanced strategies. The investigation and implementation of the following are strongly recommended:

- **PID (Proportional-Integral-Derivative) Controllers:** For more stable and precise regulation of environmental parameters, reducing oscillations and "boundary-hugging" behaviour.
- **Model Predictive Control (MPC):** Which can optimize control actions over a future horizon, considering system models and known disturbances (e.g., lighting schedules, daily ambient temperature variations).
- **Machine Learning Control (MLC):** To develop adaptive and predictive capabilities, allowing the system to learn from historical data and adjust to variable or unmodeled conditions. The prototype's robust data logging capability (Chapter 4 ) provides a basis for collecting the necessary data to train such models.

### Refinement of Actuators and Hardware

The limitations of the Peltier coolers highlight the need for more careful actuator selection. It is suggested to:

- **Investigate Alternative Thermal Management Solutions:** Test and evaluate more robust, efficient, and scalable cooling actuators, such as small heat pumps, compact air conditioning units, or evaporative cooling systems, appropriate for the volume and thermal load of the chambers.
- **Evaluate Industrial-Grade Sensors and Actuators:** To improve the reliability, precision, and durability of system components, especially for larger-scale perspectives.

- **Optimize Chamber Insulation and Design:** Improve the thermal insulation of cultivation chambers to reduce the influence of external environmental conditions and the load on climate control systems.

**Scalability and Edge Intelligence**

Although the prototype demonstrated parallel operation of two units, scalability to commercial PFs requires further investigation:

- **Architecture Load Testing:** Evaluate the performance of the Platform layer under a significantly larger number of Edge devices and data streams.
- **Implementation and Evaluation of Edge Computing:** Realize the architecture's potential for edge computing (Chapter 3.1.3), moving part of the control logic and data processing closer to the sensors and actuators. This can improve real-time responsiveness, reduce network dependency, and enable decentralized decision-making for critical control cycles.

**Development of Symbiotic Cultivation**

The successful demonstration of gas exchange opens doors for further development of symbiotic integration:

- **Optimization and Quantification of Resource Exchange:** Investigate the efficiency of $CO_2$ and $O_2$ transfer and optimize airflow mechanisms. Quantify the impact of this exchange on the growth, yield, and quality of both crops (plants and fungi).
- **Nutrient Cycling and Waste Valorisation:** Expand the concept of circularity to include nutrient cycling, for example, by testing the use of spent mushroom substrate (SMS) as fertilizer for plants or plant waste as a component of fungal substrate, as conceptually discussed (Chapter 3.2.3).
- **Optimized Design of Multi-Chamber Systems:** Develop PF designs that natively integrate multiple chambers to maximize resource synergy (gases, water, heat).

**Economic and Life Cycle Analysis**

To address a central limitation of the thesis, it is important to:

- **Conduct a Detailed Economic Feasibility Study:** Evaluate the investment and operational costs of PFs implementing the PFIoT architecture with updated components and advanced control systems. Conduct cost-benefit and return on investment analyses for different crops and scales of operation.
- **Life Cycle Assessment (LCA):** To analyse the overall environmental impact, considering energy consumption, material use, and waste management.

**Quantitative Biological Assessment**

Future iterations of the work should incorporate:

- **Quantitative Measurements:** Of growth, yield, and quality parameters of plants and fungi (e.g., biomass, nutritional content, metabolic profiles) to objectively assess the impact of different environmental recipes and control strategies, overcoming the qualitative assessment of the current prototype.

By systematically addressing these areas, future research can build upon the foundations established by this thesis, bringing Digital Plant Factories closer to becoming more efficient, sustainable, and economically viable solutions for modern food production challenges.

## 6.7 Final Considerations

This thesis aimed to address the challenges of modernizing and optimizing Plant Factories through the design and prototyping of an IoT reference architecture (PFIoT). The work successfully culminated in the presentation of a three-tier architecture, grounded in established Industrie 4.0 principles, and in the demonstration of its feasibility through a functional prototype capable of managing multiple independent cultivation units and innovatively integrating plant and fungal cultivation with the exchange of gaseous metabolic byproducts.

The findings confirmed the potential of the PFIoT architecture to promote standardization, modularity, and integration in CEA systems, crucial elements for overcoming the technological heterogeneity currently limiting the sector. The prototype's ability to operate in parallel and facilitate resource sharing between diverse types of produce, underscores the flexibility and innovative nature of the proposed approach.

However, the research also transparently exposed the inherent limitations of a small-scale implementation with low-cost components and basic control algorithms. The

suboptimal performance of certain actuators, such as the Peltier coolers, and the reactive nature of the control system in the face of disturbances, highlight the distance still to be covered to achieve operational efficiency and robust environmental control in commercial scenarios. These observations do not diminish the value of the conceptual architecture but rather critically inform the subsequent steps necessary for its maturation.

Ultimately, this thesis offers a contribution to the emerging field of Digital Plant Factories. It provides not only a validated architectural design but also a set of empirical learnings and a clear roadmap for future investigations. It is believed that by continuing to develop and refine aspects of control, hardware selection, and resource optimization, Plant Factories based on principles like those explored herein will play an increasingly vital role in ensuring a safe, sustainable, and high-quality food supply for a growing global population.

To advance the PFIoT platform towards commercial viability, future work will concentrate on several key areas. A primary objective will be to harden the platform architecture and software, enhancing robustness, and IoT security. Concurrently, a significant research effort will be dedicated to the experimentation and implementation of advanced feedback control loop algorithms, moving beyond reactive rule-based models to predictive and adaptive strategies for more precise environmental management. To address operational sustainability and cost-efficiency, the platform will be extended to monitor energy consumption in real-time. Finally, substantial improvements will be made to the User Experience and User Interface (UX/UI) to ensure the system is intuitive and easy to operate.

This research culminated in a publication, which can be found in APPENDIX, Publication.

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# APPENDIX

## A. Detailed Prototype Bill of Materials

### Bill of Materials (BOM) Table:

| Component Category | Specific Item/Model | Manufacturer | Qty | Brief Description | Thesis Reference (Chapter/Figure) |
|---|---|---|---|---|---|
| Microcontroller | ESP32-S3-DevKitC-1-N8R8 | Espressif Systems | 5 | Main controller for sensor reading and actuator control in both units | Chapter 4 Figure 39 |
| Microcontroller | FireBeetle 2 Board ESP32-S3 (N16R8) AIoT Microcontroller with Camera | DFRobot | 2 | Camera module and additional sensing | Chapter 4 Figure 40 |
| Sensor | Sensirion SCD30 ($CO_2$, Temp, Humidity) | Sensirion | 1 | Air parameter sensing in Unit 01 | Chapter 4 Figure 41 |
| Sensor | Sensirion SCD41 ($CO_2$, Temp, Humidity) | Sensirion | 1 | Air parameter sensing in Unit 02 | Chapter 4 Figure 43 |
| Sensor | DS18B20 Digital temperature sensor | Maxim Integrated | 1 | Substrate/nutrient solution temperature sensing | Chapter 4 Figure 45 |
| Actuator | UVC Ultraviolet Germicidal Lamp Strip (270-280nm) | DFRobot | 3 | Air/chamber sterilization | Chapter 4 Figure 47 |
| Actuator | PC Fan (e.g., 12V DC Brushless) | Generic | 2 | Air circulation, inter-unit gas exchange | Chapter 4 Figure 48 |
| Actuator | Heating Pad (e.g., Silicone Heater Pad,220V) | Generic | 1 | Chamber heating | Chapter 4 Figure 50 |
| Actuator | Ultrasonic Nebulizer TDK (NB-80E-01-H) | TDK | 1 | Humidification | Chapter 4 Figure 51 |
| Actuator | Peltier Cooler (12V 120W TEC) | Generic | 2 | Chamber cooling | Chapter 4 Figure 52 |
| Actuator | Grow LED Strip (Red:Blue 3:1) | Generic | 2 | Photosynthetic/ photomorphic lighting | Chapter 4 Figure 53 |
| Actuator | 8-Channel Relay Module | e.g., Adafruit | 2 | Power switching for actuators | Chapter 4 Figure 54 |
| Other | Cultivation Chambers (30x30x50 cm) | Buit based on EPS | 2 | Cultivation chambers | Chapter 4 Figure 36 |

| Component Category | Specific Item/Model | Manufacturer | Qty | Brief Description | Thesis Reference (Chapter/Figure) |
|---|---|---|---|---|---|
| Other | Ducting, wiring, power supplies, etc. | Various | - | System assembly | - |

*Table 5 Prototype Bill of Materials*

## B. Details of Main Software Implementation

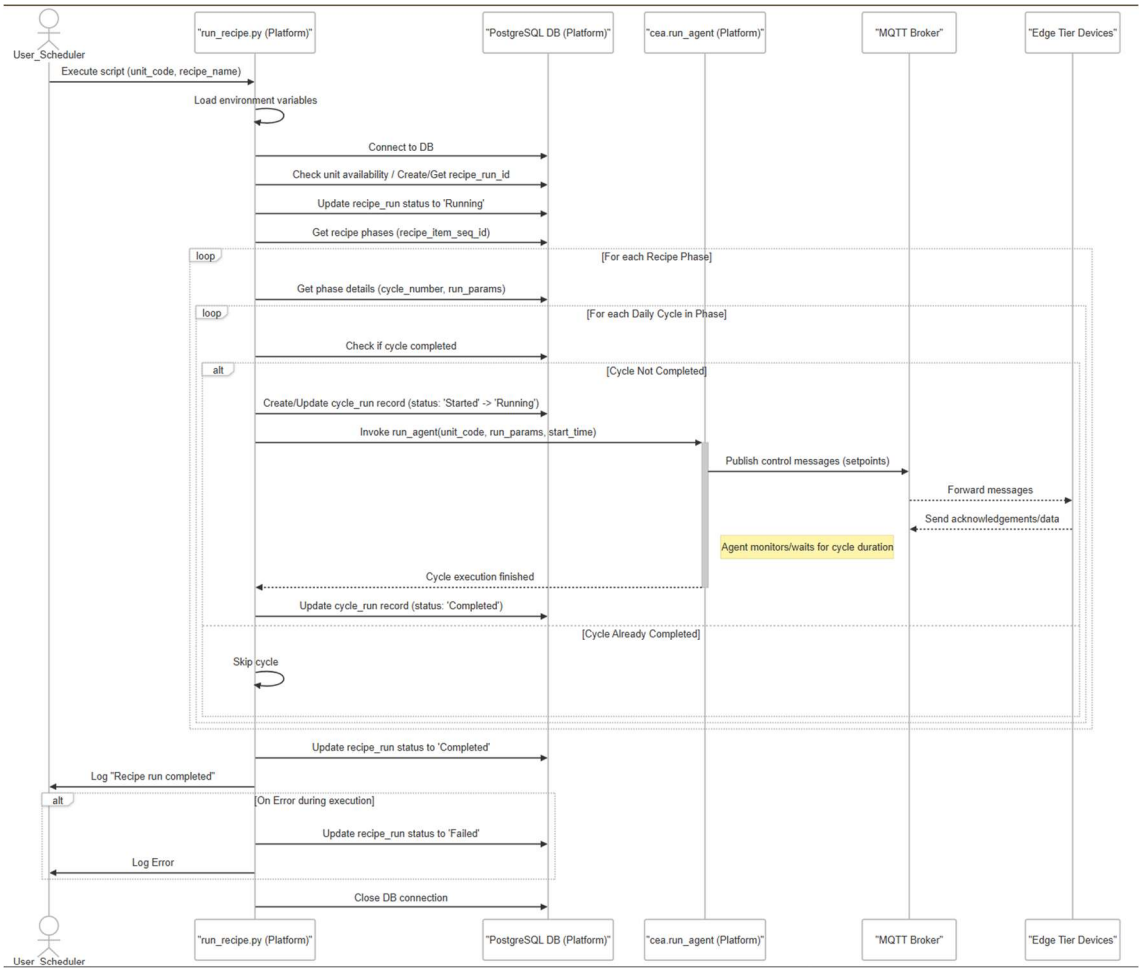



*Figure B.1 Recipe run process (Flow Swimlane Diagram)*

## C. Data Model Schema

Below contains the data definition language (DDL) of the cea database.

### C.1 cea.cea_location

```
-- Table: cea.cea_location
-- DROP TABLE IF EXISTS cea.cea_location;
CREATE TABLE IF NOT EXISTS cea.cea_location (
    location_id INTEGER NOT NULL DEFAULT
nextval('cea.cea_location_location_id_seq'::regclass),
    name CHARACTER VARYING(255) COLLATE pg_catalog."default" NOT NULL,
    address CHARACTER VARYING(255) COLLATE pg_catalog."default",
    latitude NUMERIC,
    longitude NUMERIC,
    contact_person CHARACTER VARYING(255) COLLATE pg_catalog."default",
    contact_info CHARACTER VARYING(255) COLLATE pg_catalog."default",
    description TEXT COLLATE pg_catalog."default",
    is_active cea.is_active COLLATE pg_catalog."default",
    CONSTRAINT cea_location_pkey PRIMARY KEY (location_id) USING INDEX TABLESPACE
cea_tbsp
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.cea_location OWNER TO cea_role;

COMMENT ON TABLE cea.cea_location IS 'Represents the facility where growing areas are
located.';
COMMENT ON COLUMN cea.cea_location.location_id IS 'Unique identifier for the
location.';
COMMENT ON COLUMN cea.cea_location.name IS 'Name of the farm or facility.';
COMMENT ON COLUMN cea.cea_location.address IS 'Physical address of the location.';
COMMENT ON COLUMN cea.cea_location.latitude IS 'Latitude coordinate of the
location.';
COMMENT ON COLUMN cea.cea_location.longitude IS 'Longitude coordinate of the
location.';
COMMENT ON COLUMN cea.cea_location.contact_person IS 'Contact person at the
location.';
COMMENT ON COLUMN cea.cea_location.contact_info IS 'Contact information (phone,
email) for the location.';
COMMENT ON COLUMN cea.cea_location.description IS 'Description of the facility.';
```

## C.2 cea.cea_unit

```
-- Table: cea.cea_unit
-- DROP TABLE IF EXISTS cea.cea_unit;
CREATE TABLE IF NOT EXISTS cea.cea_unit (
    unit_id INTEGER NOT NULL DEFAULT nextval('cea.cea_unit_unit_id_seq'::regclass),
    unit_type cea.unit_type COLLATE pg_catalog."default" NOT NULL,
    description CHARACTER VARYING COLLATE pg_catalog."default",
    location_id INTEGER NOT NULL,
    area DOUBLE PRECISION,
    height DOUBLE PRECISION,
    "timestamp" TIMESTAMP WITH TIME ZONE DEFAULT CURRENT_TIMESTAMP,
    is_active cea.is_active COLLATE pg_catalog."default" NOT NULL,
    unit_code CHARACTER VARYING(10) COLLATE pg_catalog."default" NOT NULL,
    CONSTRAINT unit_pkey PRIMARY KEY (unit_id) USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT unit_code_uk UNIQUE (unit_code) USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT cea_unit_location_id_fkey FOREIGN KEY (location_id) REFERENCES
cea.cea_location (location_id) MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.cea_unit OWNER TO cea_role;

COMMENT ON COLUMN cea.cea_unit.unit_id IS 'Production unit identifier.';
COMMENT ON COLUMN cea.cea_unit.area IS 'facility''s production area. Used to
calculate volume.';
COMMENT ON COLUMN cea.cea_unit.height IS 'facility''s production height. Used to
calculate facility volume.';
COMMENT ON COLUMN cea.cea_unit."timestamp" IS 'Record creation timestamp';
COMMENT ON COLUMN cea.cea_unit.unit_code IS 'Unit code, used to handle backend
processes (order to be changed)';
```

## C.3 cea.cea_zone

```
-- Table: cea.cea_zone
-- DROP TABLE IF EXISTS cea.cea_zone;
CREATE TABLE IF NOT EXISTS cea.cea_zone (
    unit_id INTEGER NOT NULL,
    zone_id INTEGER NOT NULL DEFAULT nextval('cea.cea_zone_zone_id_seq'::regclass),
    zone_code CHARACTER VARYING COLLATE pg_catalog."default" NOT NULL,
    zone_description CHARACTER VARYING COLLATE pg_catalog."default",
    timestamp_cre TIMESTAMP WITH TIME ZONE DEFAULT CURRENT_TIMESTAMP,
    is_active cea.is_active COLLATE pg_catalog."default" NOT NULL,
    CONSTRAINT cea_zone_pkey PRIMARY KEY (zone_id) USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT zone_unit_fk FOREIGN KEY (unit_id) REFERENCES cea.cea_unit (unit_id)
MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.cea_zone OWNER TO cea_role;
```

## C.4 cea.cea_component

```
-- Table: cea.component
-- DROP TABLE IF EXISTS cea.component;
CREATE TABLE IF NOT EXISTS cea.component (
    component_id INTEGER NOT NULL DEFAULT
nextval('cea.component_component_id_seq'::regclass),
    device_id INTEGER NOT NULL,
    component_type CHARACTER VARYING(8) COLLATE pg_catalog."default",
    model CHARACTER VARYING(255) COLLATE pg_catalog."default",
    manufacturer CHARACTER VARYING(255) COLLATE pg_catalog."default",
    parameters JSON,
    is_active cea.is_active COLLATE pg_catalog."default" DEFAULT 'Y'::CHARACTER
VARYING,
    timestamp_cre TIMESTAMP WITHOUT TIME ZONE DEFAULT CURRENT_TIMESTAMP,
    CONSTRAINT component_pkey PRIMARY KEY (component_id) USING INDEX TABLESPACE
cea_tbsp,
    CONSTRAINT "component-device" FOREIGN KEY (device_id) REFERENCES cea.device
(device_id) MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.component OWNER TO cea_role;

COMMENT ON TABLE cea.component IS 'Represents the Component (sensor or actuator)
installed in IoT devices used in the CEA system.';
COMMENT ON COLUMN cea.component.component_id IS 'Component identifier';
COMMENT ON COLUMN cea.component.device_id IS 'Unique identifier for the IoT device
with in CEA environment e.g same as dns name.';
COMMENT ON COLUMN cea.component.component_type IS 'Type of component use by the
device (e.g., CO2 sensor, heater actuator, etc).';
COMMENT ON COLUMN cea.component.model IS 'Model of the component.';
COMMENT ON COLUMN cea.component.manufacturer IS 'Manufacturer of the device.';
COMMENT ON COLUMN cea.component.parameters IS 'Parameters implemented by the
component.';
COMMENT ON COLUMN cea.component.is_active IS 'Current status of the device (e.g., Y
if Active,  No if Inactive).';
```

## C.5 cea.device

```
-- Table: cea.device
-- DROP TABLE IF EXISTS cea.device;
CREATE TABLE IF NOT EXISTS cea.device (
    device_id INTEGER NOT NULL DEFAULT nextval('cea.device_device_id_seq'::regclass),
    zone_id INTEGER NOT NULL,
    device_type CHARACTER VARYING(255) COLLATE pg_catalog."default" NOT NULL,
    model CHARACTER VARYING(255) COLLATE pg_catalog."default",
```

```
    manufacturer CHARACTER VARYING(255) COLLATE pg_catalog."default",
    serial_number CHARACTER VARYING(255) COLLATE pg_catalog."default" NOT NULL,
    connection_type CHARACTER VARYING(255) COLLATE pg_catalog."default" NOT NULL
DEFAULT 'WiFi'::CHARACTER VARYING,
    dns_name CHARACTER VARYING(255) COLLATE pg_catalog."default" NOT NULL,
    installation_date DATE DEFAULT CURRENT_TIMESTAMP,
    is_active cea.is_active COLLATE pg_catalog."default" DEFAULT 'Y'::CHARACTER
VARYING,
    CONSTRAINT cea_device_pkey PRIMARY KEY (device_id) USING INDEX TABLESPACE
cea_tbsp,
    CONSTRAINT dns_name_uk UNIQUE (dns_name) USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT serial_number_uk UNIQUE NULLS NOT DISTINCT (serial_number) USING INDEX
TABLESPACE cea_tbsp,
    CONSTRAINT "cea_zone-device" FOREIGN KEY (zone_id) REFERENCES cea.cea_unit
(unit_id) MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.device OWNER TO cea_role;

COMMENT ON TABLE cea.device IS 'Represents an IoT device used in the CEA system.';
COMMENT ON COLUMN cea.device.device_id IS 'Unique identifier for the IoT device with
in CEA environment e.g same as dns name.';
COMMENT ON COLUMN cea.device.zone_id IS 'Production zone of identifier';
COMMENT ON COLUMN cea.device.device_type IS 'Type of device (e.g., Control, Sense or
Both).';
COMMENT ON COLUMN cea.device.model IS 'Model of the device.';
COMMENT ON COLUMN cea.device.manufacturer IS 'Manufacturer of the device.';
COMMENT ON COLUMN cea.device.serial_number IS 'Unique serial number of the device.';
COMMENT ON COLUMN cea.device.connection_type IS 'Type of connection used by the
device (e.g., Wi-Fi, LoRaWAN).';
COMMENT ON COLUMN cea.device.dns_name IS 'Dns or IP of the device.';
COMMENT ON COLUMN cea.device.installation_date IS 'Date of device installation.';
COMMENT ON COLUMN cea.device.is_active IS 'Current status of the device (e.g., Y for
Active, N for Inactive).';
```

### C.6 cea.measurement

```
-- Table: cea.measurement
-- DROP TABLE IF EXISTS cea.measurement;
CREATE TABLE IF NOT EXISTS cea.measurement (
    measure_timestamp TIMESTAMP WITH TIME ZONE NOT NULL,
    device_id CHARACTER VARYING COLLATE pg_catalog."default" NOT NULL,
    device_dns CHARACTER VARYING COLLATE pg_catalog."default" NOT NULL,
    msg_type cea.msg_type COLLATE pg_catalog."default" NOT NULL,
    msg JSON NOT NULL,
    "timestamp" TIMESTAMP WITH TIME ZONE NOT NULL DEFAULT CURRENT_TIMESTAMP
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.measurement OWNER TO cea_role;
```

```
COMMENT ON COLUMN cea.measurement.device_dns IS 'Unique identifier for the IoT device
with in CEA environment (e.g dns name) .';
```

## C.7 cea.recipe

```
-- Table: cea.recipe
-- DROP TABLE IF EXISTS cea.recipe;
CREATE TABLE IF NOT EXISTS cea.recipe (
    recipe_id INTEGER NOT NULL,
    recipe_name CHARACTER VARYING COLLATE pg_catalog."default" NOT NULL,
    recipe_description CHARACTER VARYING COLLATE pg_catalog."default",
    timestamp_cre TIMESTAMP WITH TIME ZONE NOT NULL DEFAULT CURRENT_TIMESTAMP,
    timestamp_upd TIMESTAMP WITH TIME ZONE,
    CONSTRAINT recipe_pkey PRIMARY KEY (recipe_id) USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT recipe_name_uk UNIQUE (recipe_name) USING INDEX TABLESPACE cea_tbsp
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.recipe OWNER TO cea_role;

-- Index: idx_recipe_recipe_id
-- DROP INDEX IF EXISTS cea.idx_recipe_recipe_id;
CREATE INDEX IF NOT EXISTS idx_recipe_recipe_id ON cea.recipe USING btree (recipe_id
ASC NULLS LAST) TABLESPACE cea_tbsp;
```

## C.8 cea.recipe_line

```
-- Table: cea.recipe_line
-- DROP TABLE IF EXISTS cea.recipe_line;
CREATE TABLE IF NOT EXISTS cea.recipe_line (
    recipe_id INTEGER NOT NULL,
    recipe_item_seq_id INTEGER NOT NULL,
    recipe_item_seq_name CHARACTER VARYING COLLATE pg_catalog."default" NOT NULL,
    cycle_number INTEGER NOT NULL,
    air_temperature_lower_limit INTEGER NOT NULL,
    air_temperature_upper_limit INTEGER NOT NULL,
    light_type cea.light_types COLLATE pg_catalog."default" NOT NULL,
    light_on_minutes INTEGER NOT NULL,
    light_off_minutes INTEGER NOT NULL,
    co2_lower_limit INTEGER NOT NULL,
    co2_upper_limit INTEGER NOT NULL,
    hr_lower_limit INTEGER NOT NULL,
    hr_upper_limit INTEGER NOT NULL,
    timestamp_cre TIMESTAMP WITH TIME ZONE NOT NULL DEFAULT CURRENT_TIMESTAMP,
    timestamp_upd TIMESTAMP WITH TIME ZONE,
    substrate_temperature_lower_limit INTEGER,
    substrate_temperature_upper_limit INTEGER,
    notes CHARACTER VARYING COLLATE pg_catalog."default",
    CONSTRAINT recipe_line_pkey PRIMARY KEY (recipe_id, recipe_item_seq_id) USING
INDEX TABLESPACE cea_tbsp,
    CONSTRAINT recipe_id_fk FOREIGN KEY (recipe_id) REFERENCES cea.recipe (recipe_id)
MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.recipe_line OWNER TO cea_role;

-- Index: idx_recipe_line_recipe_id_item_seq_id
-- DROP INDEX IF EXISTS cea.idx_recipe_line_recipe_id_item_seq_id;
CREATE INDEX IF NOT EXISTS idx_recipe_line_recipe_id_item_seq_id ON cea.recipe_line
USING btree (
    recipe_id ASC NULLS LAST,
    recipe_item_seq_id ASC NULLS LAST
) TABLESPACE cea_tbsp;
```

## C.9 cea.recipe_line_cycle_run

```
-- Table: cea.recipe_line_cycle_run
-- DROP TABLE IF EXISTS cea.recipe_line_cycle_run;
CREATE TABLE IF NOT EXISTS cea.recipe_line_cycle_run (
    recipe_line_cycle_run_id INTEGER NOT NULL DEFAULT nextval(
        'cea.recipe_line_cycle_run_recipe_line_cycle_run_id_seq'::regclass
    ),
    recipe_run_id INTEGER NOT NULL,
    recipe_id INTEGER NOT NULL,
    recipe_item_seq_id INTEGER NOT NULL,
    recipe_item_seq_cycle_num INTEGER NOT NULL,
    recipe_line_seq_cycle_run_start TIMESTAMP WITH TIME ZONE NOT NULL DEFAULT
CURRENT_TIMESTAMP,
    recipe_line_seq_cycle_run_end TIMESTAMP WITH TIME ZONE,
    recipe_line_cycle_run_status cea.run_status COLLATE pg_catalog."default" NOT
NULL,
    run_params JSON,
    timestamp_cre TIMESTAMP WITH TIME ZONE NOT NULL DEFAULT CURRENT_TIMESTAMP,
    timestamp_upd TIMESTAMP WITH TIME ZONE,
    CONSTRAINT recipe_line_cycle_run_pkey PRIMARY KEY (recipe_line_cycle_run_id)
USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT recipe_line_cycle_run_uk UNIQUE (
        recipe_run_id,
        recipe_id,
        recipe_item_seq_id,
        recipe_item_seq_cycle_num
    ) USING INDEX TABLESPACE cea_tbsp,
    CONSTRAINT "recipe_line-recipe_line_cycle_run" FOREIGN KEY (recipe_id,
recipe_item_seq_id) REFERENCES cea.recipe_line (recipe_id, recipe_item_seq_id) MATCH
SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION,
    CONSTRAINT "recipe_run-recipe_line_cycle_run" FOREIGN KEY (recipe_run_id)
REFERENCES cea.recipe_run (recipe_run_id) MATCH SIMPLE ON UPDATE NO ACTION ON DELETE
NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.recipe_line_cycle_run OWNER TO cea_role;

-- Index: idx_rlcr_run_id_recipe_id_item_seq_id_cycle_num
-- DROP INDEX IF EXISTS cea.idx_rlcr_run_id_recipe_id_item_seq_id_cycle_num;
CREATE INDEX IF NOT EXISTS idx_rlcr_run_id_recipe_id_item_seq_id_cycle_num ON
cea.recipe_line_cycle_run USING btree (
    recipe_run_id ASC NULLS LAST,
    recipe_id ASC NULLS LAST,
    recipe_item_seq_id ASC NULLS LAST,
    recipe_item_seq_cycle_num ASC NULLS LAST
) TABLESPACE cea_tbsp;
```

## C.10 cea.recipe_run

```
-- Table: cea.recipe_run
-- DROP TABLE IF EXISTS cea.recipe_run;
CREATE TABLE IF NOT EXISTS cea.recipe_run (
    recipe_run_id INTEGER NOT NULL DEFAULT
nextval('cea.recipe_run_recipe_run_id_seq'::regclass),
    recipe_id INTEGER NOT NULL,
    unit_id INTEGER NOT NULL,
    recipe_run_start TIMESTAMP WITH TIME ZONE NOT NULL,
    recipe_run_end TIMESTAMP WITH TIME ZONE,
    timestamp_cre TIMESTAMP WITH TIME ZONE NOT NULL DEFAULT
CURRENT_TIMESTAMP,
    timestamp_upd TIMESTAMP WITH TIME ZONE,
    recipe_run_status cea.run_status COLLATE pg_catalog."default" NOT NULL,
    is_active cea.is_active COLLATE pg_catalog."default" NOT NULL,
    CONSTRAINT recipe_run_pkey PRIMARY KEY (recipe_run_id) USING INDEX
TABLESPACE cea_tbsp,
    CONSTRAINT "cea_unit-recipe_run" FOREIGN KEY (unit_id) REFERENCES
cea.cea_unit (unit_id) MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION,
    CONSTRAINT "recipe-recipe_run" FOREIGN KEY (recipe_id) REFERENCES
cea.recipe (recipe_id) MATCH SIMPLE ON UPDATE NO ACTION ON DELETE NO ACTION
) TABLESPACE cea_tbsp;

ALTER TABLE IF EXISTS cea.recipe_run OWNER TO cea_role;

-- Index: idx_recipe_run_recipe_id
-- DROP INDEX IF EXISTS cea.idx_recipe_run_recipe_id;
CREATE INDEX IF NOT EXISTS idx_recipe_run_recipe_id ON cea.recipe_run USING
btree (recipe_id ASC NULLS LAST) TABLESPACE cea_tbsp;

-- Index: idx_recipe_run_run_id
-- DROP INDEX IF EXISTS cea.idx_recipe_run_run_id;
CREATE INDEX IF NOT EXISTS idx_recipe_run_run_id ON cea.recipe_run USING
btree (recipe_run_id ASC NULLS LAST) TABLESPACE cea_tbsp;

-- Index: idx_recipe_run_status_recipe_id
-- DROP INDEX IF EXISTS cea.idx_recipe_run_status_recipe_id;
CREATE INDEX IF NOT EXISTS idx_recipe_run_status_recipe_id ON cea.recipe_run
USING btree (
    recipe_run_status COLLATE pg_catalog."default" ASC NULLS LAST,
    recipe_id ASC NULLS LAST
) TABLESPACE cea_tbsp;
```

### D. Publication

The current research resulted in the publication of the article "Future of Farming: An Architecture for Industrie 4.0 in Plant Factories," presented at the Third International Conference on Industry 4.0 2025 (https://www.vit.edu/I4Tech2025), held at the Vishwakarma Institute of Technology, Pune, India.




*Figure 64 the Third International Conference on Industry 4.0*




*Figure 65 - Conference Participation Certificate.*

# Future of Farming: An Architecture for Industrie 4.0 in Plant Factories

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*Abstract—*

**The future of food and agriculture faces uncertainty regarding its sustainability and performance. In this context, Plant Factories (PFs)—a subclass of Controlled Environment Agriculture analogous to industrial manufacturing—offer a solution for crop production with full control over input variables such as $CO_2$, light, temperature, water, and nutrients. However, the PF industry is impeded by high operational costs and a lack of technological standardization, which increases investment risk and limits interoperability. This paper argues that digital transformation concepts such as Industrie 4.0 are essential for the sector's evolution, as their underlying enablers like the Internet of Things, Automation, and Big Data are the same as those required in Plant Factories. This work proposes an IoT reference architecture for PFs, aiming for standardization, effective control, and the potential integration of diverse cultivation types. This architectural blueprint provides a foundation for developing robust, scalable, and economically viable digital infrastructures, which are critical for unlocking the full potential of PFs.**

***Keywords—Precision Agriculture, IoT, sustainability, Plant Factories, Industrie 4.0, Reference Architecture.***

## I. INTRODUCTION

The future of global food production faces unprecedented uncertainty [1]. Factors such as climate change, the depletion of natural resources, pollution, relentless population growth, and shifting consumer dietary patterns collectively challenge the sustainability and performance of current agricultural systems [1]. With the global population projected to reach 8.4 billion by 2030 [2], a fundamental shift away from conventional practices is required. The Food and Agriculture Organization (FAO) emphasizes that "business as usual" is not a viable option, necessitating a transition towards innovative agricultural strategies that ensure sustainability while meeting escalating food demands [1]

In this context, Controlled Environment Agriculture (CEA) emerges as a promising approach [3], [4]. A specific subclass of CEA, the Plant Factory (PF), is the focus of this research [5]. PFs, often utilizing artificial lighting (PFAL), represent a paradigm shift towards producing crops indoors, independent of external climate conditions and geographical limitations [6][7]. These facilities typically involve cultivating plants in vertically stacked layers using soilless techniques within thermally insulated, near-airtight structures [7]. This approach allows for meticulous control over environmental variables such as temperature, humidity, carbon dioxide ($CO_2$) concentration, light spectrum and intensity, water, and nutrient delivery [6].. The analogy used with industrial manufacturing is intentional, as that sector has already been subject to digital disruption captured in concepts such as Industrie 4.0, whose underlying supporting enablers are the same as those required in Plant Factories [6].

## II. PROBLEM STATEMENT: THE VIABILITY CRISIS IN PLANT FACTORIES

The advantages are compelling: year-round crop production independent of weather, significantly reduced water consumption (up to 95% less), elimination of pesticides, and the ability to locate farms in urban centres, drastically shortening the supply chain [7], [9]. Despite this promise, the industry stands at a perilous crossroads.

Despite their potential, Plant Factories face significant hurdles that impede widespread adoption and long-term success [10]. A primary challenge lies in the substantial costs associated with establishing and operating these facilities [40]. Initial installation costs can be significantly higher than traditional greenhouses, while operational costs, particularly energy consumption for lighting and climate control, remain a major concern [11][7]. Electricity accounts for a substantial portion (18-21%) of total production costs [11].

The economic viability and sustainability of PFs are under scrutiny, evidenced by a recent wave of bankruptcies among prominent PF companies between 2022 and 2024, including Glowfarms, Fifth Season, Future Crops, Kalera, AeroFarms, AppHarvest, and Bowery Farming [12], [9], [14], [11], [16], [17], [18]. These failures are often attributed to high operating costs, an overreliance on venture capital, limited crop diversity, and intense market competition [12], [13], [14], [15], [16], [17].

Beyond economics, technological challenges persist [15]. The PF industry currently lacks standardization in its technological platforms and Internet of Things (IoT) implementations [20], [21], [22]. This heterogeneity leads to difficulties in system integration, limits interoperability between components from different vendors, increases investment risks, and hinders the development of scalable, cost-effective solutions [20], [17], [24], [8]. There is a clear need for optimized, standardized, and robust digital infrastructures to unlock the full potential of PFs.

## III. THE INDUSTRIE 4.0 FRAMEWORK FOR DIGITAL AGRICULTURE

Plant factories share the same challenges and opportunities as any other industry digitizing its production processes and could be seen as fitting perfectly in the Industrie 4.0 concept [20]. Therefore, the commonly accepted design principles for

Industrie 4.0 provide a high-level framework for implementation:

- Interoperability: The ability of all system elements, such as devices, sensors, machines, and people, to interconnect as a collaborative ecosystem [25], [26], [5], [27], [28].
- Virtualization: The implementation of Cyber-Physical Systems (CPS) which integrate sensing, computation, control, and networking into physical objects, resulting in a digital copy of the physical world known as a Digital Twin [25].
- Decentralization: The ability of CPSs to work independently, making autonomous decisions in real-time while constrained by organizational goals [25], [5], [27], [28].
- Real-Time Capability: Perpetual connectivity that allows for continuous data capture, monitoring, real-time analytics, and fast, automated decision-making [25], [5], [27], [28].
- Service-Orientation: The shift of the human role from operator to decision-maker, requiring systems that aggregate and present information in a comprehensive fashion to assist in the decision-making process [27].
- Modularity: The ability of factories to agilely adapt the production process to meet new market demands, which is critical for integrating machinery from different vendors [25], [5], [27], [28].

Applying these pillars in an integrated fashion is the key to creating an intelligent, autonomous, and efficient Plant Factory. However, this integration is impossible without a common language: standardization. Recognizing this need, the Plant Factory IoT (PFIoT) Reference Architecture is introduced as a standardized framework to guide the development and implementation of intelligent plant factories.

## IV. A Proposed PFIoT Reference Architecture

The complexity of IIoT systems requires a reference framework to capture and structure stakeholders' requirements, allowing for an open, repeatable, and functional architecture. This research proposes mapping concepts from Reference Architectural Model Industrie 4.0 (RAMI 4.0) and Industrial Internet Reference Architecture (IIRA) into a three-tier system architecture (Figure 1) to support PFs.

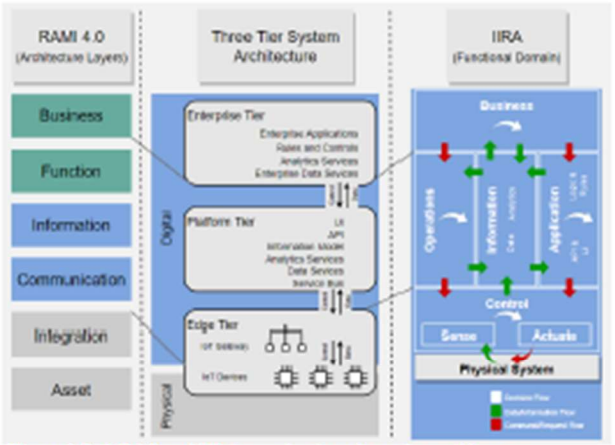



*Figure 1 RAMI 4.0 and IIRA mapping into three-tier architecture*

The proposed logical system architecture (Figure 2) provides a blueprint for organizing the different macro-components to be implemented.

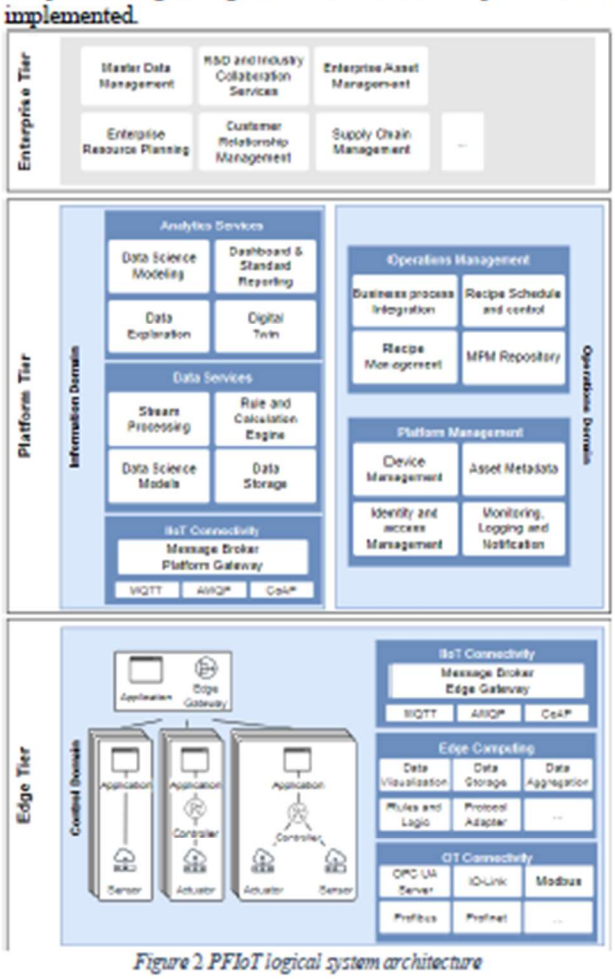



*Figure 2 PFIoT logical system architecture*

### A. The Edge Tier: The Physical-Digital Interface

The Edge Tier represents the different edge nodes attached to assets, capacitated to control the physical environment through a sense-and-actuate loop. It is the heartbeat of the IIoT architecture where data is continuously collected, and control commands are received. This tier must comprehend integration and communication capabilities (OT and IIoT Connectivity) as well as computing and storage capabilities to enable edge intelligence. The Edge Tier is comprised of:

- Operational Technology (OT) Connectivity: This includes Industrial Ethernet protocols (e.g., Profinet, EtherCAT), data exchange frameworks (e.g., OPC UA), and sensor/actuator connection standards (e.g., IO-Link).
- Edge Computing: This includes a collection of resources to aggregate and route data from OT to the IT space and, inversely, submit commands from IT to OT. Moving computational capabilities to edge nodes makes CPSs less susceptible to latency issues or access disruption.
- IIoT Connectivity: To ensure interoperability, edge nodes are decoupled and interact via an Edge Gateway using messaging protocols such as MQTT, AMQP, or CoAP.

### B. The Platform Tier: The System's Central Brain

The Platform Tier acts as the central brain of the IIoT architecture, receiving data from the Edge tier to be processed, contextualized, and used to generate knowledge that is subsequently applied as actions on the physical environment. It is composed of several key services organized into two primary domains: the Information Domain and the Operations Domain.

- **Data Services**: Residing in the Information Domain, these services are responsible for handling the data lifecycle once it is received via IIoT Connectivity. They focus on the processing, transformation, contextualization, and persistent storage of data to ensure its quality, usability, and accessibility. Key responsibilities include parsing incoming messages, routing data to appropriate storage or processing pipelines, and structuring it according to a defined Plant Factory Data Model.
- **Analytics Services**: This component, also in the Information Domain, provides users with the tools necessary for data visualization, monitoring, and in-depth analysis of the system's performance. It leverages the data collected by Data Services to offer insights into environmental conditions and actuator behaviour. The primary interface for these services is typically a dashboard that allows for the visualization of time-series data against recipe parameters.
- **Platform Management:** As part of the Operations Domain, Platform Management is responsible for the provisioning, management, and monitoring of all elements in the platform, such as devices, applications, and users. Its key functions include device management (covering the entire asset lifecycle), managing asset metadata, identity and access management for users and applications, and the monitoring, logging, and notification of all relevant platform activities.
- **Operations Management:** Also in the Operations Domain, this component focuses on the tools for effective planning, execution, and monitoring of day-to-day cultivation activities. It translates production goals into actionable tasks, such as the detailed definition and administration of cultivation recipes and the scheduling of their execution across production units.

### C. The Enterprise Tier: Business Integration and Strategy

This tier fulfills different business domain applications and decision support systems that as a whole reflect business objectives, constraints, and products. It includes systems for Enterprise Resource Planning, Customer Relationship Management, Supply Chain Management, and R&D Collaboration Services. The Platform tier reports back operational information useful for enterprise functions like asset performance management and overall business analytics.

## V. THE RATIONALE FOR STANDARDIZATION

The current PF landscape is characterized by a heterogeneity of technological implementations and a lack of common standards, which results in higher investment requirements and associated risk. Overcoming this challenge is not merely an exercise in technical alignment but a crucial economic imperative. A large body of research conducted across numerous countries—including Canada, France, Germany, and the United Kingdom—has consistently found a positive correlation between a nation's "stock of standards" and its economic growth, whether measured by GDP or labour productivity [29], [30] For example, studies have attributed as much as 0.7% of the UK's GDP and 0.8% of France's GDP to the influence of standards[29]. This economic impact is driven by standards serving as a key component of an economy's "knowledge stock," making the use of capital and labour more efficient[29]. Knowledge transfer from more mature concepts like Industrie 4.0 is a huge opportunity for the PF sector [6] and embedding standards into the innovation process is the means for achieving agile and fast technological adoption [23], [31]. The rationale is built on the following pillars:

### A. Reduced Integration Costs and Enhanced Interoperability

In modern industrial systems, components must be interoperable. Without a "common language," connecting machines, sensors, and software from different vendors requires custom-built interfaces, leading to unmanageable complexity and a high total cost of ownership. Standards support market efficiency by preventing market failure in technology diffusion and facilitating "network externalities," where the value of technology increases as more people use it [29]. Interoperability standards ensure that technologies can interact, leading to increased value and greater market

efficiency. By establishing standardized communication protocols, the need for bespoke programming is eliminated, which reduces production costs, lowers transaction costs, and accelerates the time-to-value for new equipment.

### B. *Improved Data Accessibility Through Information Dissemination*

The primary function of standards is to serve as a vehicle for information dissemination within an economy, codifying state-of-the-art knowledge and making it equally available to everyone [29]. In a PF context, a lack of standards creates data silos, making it difficult to analyze data across the factory floor, and reconstructing past productions. By enforcing standardized communication protocols and a common information model, data from all connected assets becomes uniformly structured and accessible. This real-time capability allows for continuous data capture and provides a comprehensive view of production processes, enabling operators, managers and crop scientists to make informed, data-driven decisions and while allowing for continuous improvement.

### C. *Facilitated Scalability and a Fostered Innovation Ecosystem*

Proprietary systems lock manufacturers into specific vendors, making it difficult and expensive to scale operations. Open standards facilitate innovation by establishing a stable "playing field" on which new products and services can be built. This avoids vendor lock-in, encourages a competitive technological ecosystem, and results in a faster pace of innovation and lower costs. Surveys of businesses confirm that standards improve market access, enhance competitiveness in global markets, and facilitate the commercialization of innovative products [29]. This allows PFs to adapt quickly to market demands and rapidly adopt new technologies from a diverse range of suppliers.

### D. *Mitigated Security Risks and Enhanced Reputation*

The integration of IIoT systems and the convergence of IT and OT introduce significant complexity and expand the attack surface, creating security risks that can propagate throughout the production system. A "common security" approach, guided by standards, is fundamental for protecting business information and operational integrity[32]. Adopting established cybersecurity frameworks, such as the IEC 62443 series for industrial control systems, is critical [32]. Beyond risk mitigation, the use of standards has been shown to improve product quality, reduce waste, and enhance a company's reputation and status in the market[29].

## VI. CONCLUSION

This work has established that for Plant Factories (PFs) to evolve from promising ventures into vital components of modern production, they must adopt the operational rigor and technological discipline of mature industries. The transfer of concepts, technologies, and most importantly, standards from the Industrie 4.0 framework is not merely an opportunity for optimization but an emerging and critical necessity.

This necessity is driven not only by economic pressure but also by inevitable regulatory demands. As PFs become more integrated into food supply chains, they will be subject to the same scrutiny as traditional food producers, requiring certifiable proof of safety and quality. This mandates complete production traceability, i.e. the ability to track every input and environmental parameter from seed to harvest for any given batch. Simultaneously, for a PF to be validated, it must demonstrate full auditability, where every process is transparent, and every action within the control system is logged and verifiable. An I4.0 architecture, with its standardized data models and communication protocols, is expressly designed to provide this level of granular tracking and create an immutable audit trail.

These requirements for traceability and auditability will be magnified exponentially when considering the cultivation of organisms for pharmaceutical or nutraceutical applications—such as medicinal cannabis, psilocybin-producing fungi, or plants engineered for specific metabolites. In these highly regulated sectors, absolute proof of process control, traceability, and system auditability is non-negotiable for product validation and certification. Therefore, a strategic commitment to standardization is the essential path forward to ensure Plant Factories can achieve the security, reliability, and certified performance demanded of critical infrastructure in the future of both food and medicine.

Having established the need and the architectural blueprint, this paper marks the foundational step for the next logical and crucial phase of this work: moving from theoretical design to practical application. Future efforts will be dedicated to implementing the proposed PFIoT Reference Architecture in a real-world setting to validate its performance, scalability, and economic viability. Ultimately, a strategic commitment to standardization, realized through this implementation, is the essential path forward to ensure Plant Factories can achieve the security, reliability, and certified performance demanded of critical infrastructure in the future of both food and medicine.

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