POLITECNICO DI TORINO

Master degree course in Engineering and Management

Master Degree Thesis

Light intensity analysis for Vertical Farming: a lettuce case study

Advisors
Prof.ssa Giulia Bruno
Prof. Franco Lombardi

Candidate
Noemi Cambriglia

Academic Year 2022-2023

Contents

List of Figures

List of Tables

Introduction

The global human population is increasing year after year of about 85 million people annually, or 1.1% per year. In the 2022 the population was 8 billion, but it is expected to be about 9 billion in 2037 and 9.5 billion in 2050, with India the most populated country in the world with 1.7 billion of people. Consequently, the food demand is expected to rise by 57% to 98% by 2050 [1.0]. The challenge is to find an alternative way to cultivate to increase productivity for the growing population, without compromising the availability of natural resources, which are already limited, such as water and land.

Vertical Farming (VF) is a new technique which has been developed with the aim to reduce the environmental impact of agriculture while increasing productivity. This is an innovative urban indoor cultivation method, aimed to optimise the use of the space in the vertical dimension, without the use of soil and with the reduction of the consumption of water [3.9]. This technique is based on Controlled Environmental Agriculture (CEA) technology in which the environmental factors in the systems are controlled through IoT sensors.

This thesis work has been developed in collaboration with Technophylla srl, a start-up focused on the application of the Industry 4.0 on the agricultural sector, and the research work, conducted by the Polytechnic of Turin. The work is focused to analyse the growth chamber built in the areas of the university. In particular, the main arguments treated are the manage of the light for the growth of the plants, the IoT architecture developed for the system and two alternatives of ER Diagrams for the future upload of the databases for the collection and the analysis of the data.

The document is divided into six different chapters, starting from the theoretical argument to the experimental ones.

The first chapter is focused on the description and the analysis of the Vertical Farming starting with a section dedicated to the comparison with the Greenhouses and one dedicated to the advantages and the disadvantages of this technique. Subsequently, numerous sections are dedicated to the presentation of the possible different setup, the Hydroponic, the Aeroponic and the Aquaponic systems. An important focus is given to all the conditions necessary for the growth of the plants, as the nutrient solutions and the growing substrate, which depends on the species of the plants sowed. The last section of the chapter, is dedicated to the light, which plays an important part in the growth of the plants, because in the Vertical Farming, it has to substitute the role of sunlight in the conventional cultivation.

The firm Technophylla srl, a start up born in 2022, is presented in the second chapter. It is a spin-off of another company, Orchestra srl, which provides technologies, which are part of the Industry 4.0, to be applied on machines and production plants. Moreover, the IoT solution designed and supplied by Technophylla, SMARTFarming4.0, is described, focusing on how it can be used and who can be interested to this solution. In addition to the product, Technophylla is engaged on a project, PhyllaLab, which has the aim to obtain horticultural products with higher nutritional value and improved organoleptic properties both in greenhouse and in vertical farms. The firm has also set numerous goals to be reached for the 2030, focused on the sustainability, as the protection of the environment and the increase of energy efficiency.

The third chapter is dedicated to the definition of what is the IoT architecture and how it has been developed for the experiment conducted at the Polytechnic of Turin in the growth chamber. In particular, it is shown as the structure of an IoT architecture, based on the ISA-95, is characterized by five layers, starting from the bottom level, the zero one, as the production process, ending at the level 4, which is the business planning and logistics. This pyramid has been developed for system analysed, focusing on the components: the sensors, the actuators, the microprocessor and the software. At the end of the chapter, a technical scheme of the chamber shows the location of all the elements.

An ER Diagram for the collection and the analysis of the data has been developed in the fourth chapter. After a theoretical presentation of the model, a diagram, that can also be used in the case in which there are more than one chamber for the growth of the plants, has been built.

The experiment has been described in the fifth chapter, listing the analysis performed, with the quantity of grams necessary for the conduction of the experiment, with the aim to compare them during the three weeks of plant growth. The analysis conducted can be divided in two different phases. In the first one, particular attention is given to the setup of the chamber, analysing the light intensity in the different areas of the plant bed, depending the height of the LEDs. The objective is to uniform the light in the plant bed, using also some reflective panels. In order to decide the optimal setup, the mean value, the standard deviation and the difference between the maximum and the minimum value have been calculated. After choosing the height of the LEDs, the second phase of the analysis started with the decision of the layout. In particular, it has been defined where the plants have to be sowed and which of them and when have to be harvested. Two different layout has been proposed, one with two different experiment on the same plant bed, and one with an unique experiment. Only the second one allows to have the plant weight needed for the analysis.

The last chapter is dedicated to the conclusion of this thesis work focusing on the issues presented during the experiment and how they have been solved, on the limitation of the project and on the possible future steps, which can be performed in order to obtain results and improvements.

Chapter 1

Vertical Farming

Vertical Farming (VF) is an innovative cultivation method, which is applied indoor with a controlled-environment agriculture (CEA) technologies, such as artificial grow lighting. The main goal of this technique of cultivation is to optimize the use of the space, developing in height, in order to increase the crop yield to satisfy the request of agricultural food and to ensure food safety. However, the method is used not only for food production, but also in the pharmaceutical sector, which includes functional foods, botanicals and extracts, thanks to the controlled environment, that permits to reach the desired conditions for the growth of the plants.
This type of cultivation approach can be considered as a mix of low-cost vertical greenhouse and micro-gardening system [1.0].

The concept of the modern vertical farming was proposed in 1999 by Dickson Despommier, professor at the Mailman School of Public Health and the College of Physicians and Surgeons, Columbia University. The professor and his students have designed a skyscraper, that could feed 50,000 people. This project has popularized the concept of vertical farming.

The VF could be integrated in different buildings, such as skyscrapers, transport containers, roofs of houses or supermarkets and so on. All these solutions are part of the so called *Urban Farming*, which consists in re-purposing the available urban spaces to grow food and distributing them in the cities [1.2]. Nowadays, there are several systems all over the world, even if a lot of them are concentrated in determined geographical area. Singapore, for example, is one of the most developed city for what concern this type of cultivation. In 2012 the world's first commercial vertical farm was build by Sky Greens Farms in Singapore, in order to reduce the dependence on the imported produce. This farm produce about 1 ton of fresh veggie every other day, which are then sold in the local supermarkets [1.3].

1.1 Vertical Farming vs Greenhouse

Usually, vertical farming and greenhouse are two technologies that are confused. Despite both methodologies are considered as indoor farming, they are different in numerous aspects, such as resource use, cost, output and the optimal location for each of them. As described above, vertical farming is a more recent indoor cultivation method, characterized by floor-to-ceiling towers, as shown in figure 1.1, by artificial lighting and by the controlled-environment with the use of sensors for different parameter, like temperature and humidity. On the other hand, the greenhouses are the most traditional technology, composed by a single-layer of crops with walls and ceiling made of glass or plastic to allow natural light in, as shown in figure 1.2. In certain situations, the sun-light can be integrated by artificial light, as LEDs. However, also in the greenhouses is important to monitor the temperature, moisture and humidity, because, due to transparent ceilings and walls, the sunlight is converted in heat, resulting in a too hot and dry environment for the plants [1.4]. Vertical farming are implemented in an urban contest, in which there is limited space and limited access to fresh water. By contrast, the greenhouses are the best option in areas with unlimited spaces and lots of sun-light [1.5].
Vertical farming and greenhouses have some similarities, as high levels of environment control, ability to grow plants year-round or plants in unusual parts of the world and advances systems for moisture, humidity, nutrient and temperature control [1.4].

Figure 1.1: Vertical farming [1.6]

Figure 1.2: Greenhouse [1.7]

1.2 Advantages and Disadvantages

Vertical Farming presents some advantages and disadvantages over traditional farming. Some of the most important environment and social benefits, listed by Dickson Despommier in his book *The Vertical Farm: Feeding the World in the 21st Century* [1.8], are the following:

1. Continuous Crop Production: in the case of the VF the effect of the seasonality is absent due to the controlled-environment, which permits to create the perfect conditions in order to cultivate during all the year;

2. Elimination of Herbicides and Pesticides: veggies, in contrast with traditional farming, are produced indoor without the use of soil. Therefore, the use of pesticides and herbicides is not necessary because crops are not subject to stresses like pests. Moreover, the elimination of the use of herbicides and pesticides for food is a good quality for the population's health;

3. Protection from Weather-Related Variations in Crop Production: since veggies are cultivated indoor, they are not subject to environmental factors such as floods, hail, drought and other climatic conditions.

4. Higher Productivity: thanks to the vertical use of the buildings, the yield per unit in vertical farming is much higher than in the traditional farming. According to the species taken into account, the ratio of used acre between VF and traditional farming changes. For example, for the strawberries in order to

obtain the same quantity of products realized in one vertical farm acres, are necessary 30 soil-based acres;

5. Water Conservation and Recycling: the techniques used in vertical farms help to reduce the use of water, permitting to consume a lower quantity of water than in normal agriculture;

6. Climate Friendly: indoor agriculture reduces the use of vehicles, such as tractors and farms equipment, lowering the burning of fossil fuels. Moreover, the vegetables as easily accessible for the urban population, so also the distances covered by the trucks for the shipment are smaller, permitting to reduce the carbon dioxide emissions.

Despite the many advantages described above, there are some agricultural experts which are skeptical about the effective convenience of the vertical farming. Overall, there are two main aspects which are critical: the initial costs for the building and the high electricity usage, which can compromise the benefits of the vertical farming.

The main weaknesses of this indoor cultivation method are [1.9]:

1. Land and Building Costs: if there are not disused buildings available for the vertical farming, it is necessary to build from scratch, which can be very expensive, especially in urban areas;

2. Energy Use: the energy consumption is particular high due to the equipments necessary for the controlled environment, such as artificial lighting and climate control;

3. Limited Number of Crop Species: currently, the species which can be cultivated in the indoor agriculture are limited. Nowadays, the crops plant in vertical farms present specific characteristics, such as rapid-growing, small-footprint quick-turnover and high-value. Moreover, the choice of the veggies to be cultivated depends on the dimensions of the plant, because the biggest ones are not allowed for the limited spaces. Consequently, the range of vegetables from which select is limited to plants which can reach 30-40cm of height in order to optimize the productivity. Lettuce is the most cultivated species, followed by basil and other salad items. Slower-growing vegetables, as grains, are not as profitable in a commercial vertical farm system. The main crop types in percentages of them being produced are: leafy greens (57%), tomatoes (16%), herbs (11%), flowers (10%) and micro greens (6%);

4. Pollination Needs: the crops which needs insect pollination are less used in vertical farm, because insects are excluded from the growing environment.

Consequently, plants requiring pollination need to be pollinated by hand, requiring time and labor;

5. Controversy over USDA Organic Certification: the products grown in vertical farm would have difficulty to be certificated as Organic because the requirement about the 'soil biological activity' cannot be followed, since soil is not present in vertical farming production.

1.3 Techniques used in Vertical Farming

Vertical farms are designed in different shapes and sizes, from simple two-level to large warehouses multi stories tall. In any case, all vertical farms use one of the three different schemes that are soil less in order to provide nutrients to crops: Hydroponics, Aeroponics and Aquaponics.

In figure 1.3, there is shown the classification of soil-less farming, as described in this section. Many of these systems were invented in recent years thanks to the increasing use of soil-less agriculture.

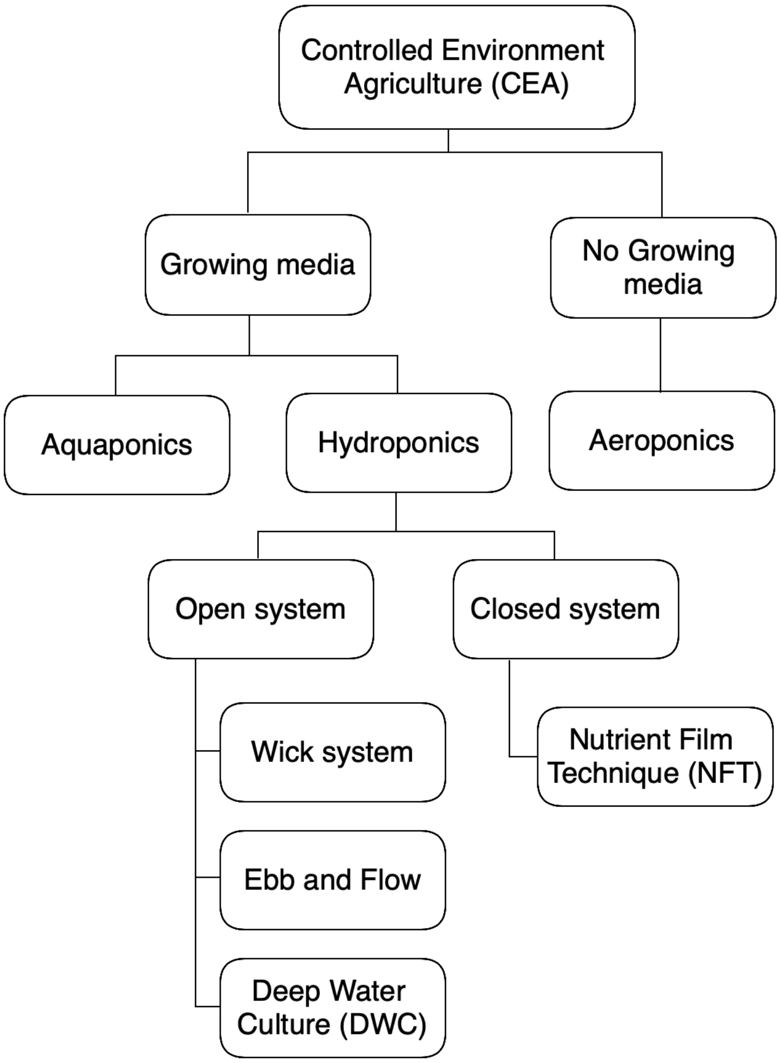

Figure 1.3: Classification of different methods of Controlled Environment Agriculture (CEA) [3.9]

1.3.1 Hydroponics

The word 'hydroponic' derives from the roots 'hydro', which means water, and 'ponos', which stands for labour. The hydroponic system is the most growing system used nowadays in vertical farms, which uses only water, nutrients and a growing medium, without the need of soil.

The plant roots, as shown in figure 1.4 are submerged in a water based solution rich of nutrients, which is constantly monitored and recirculated in order to sustain

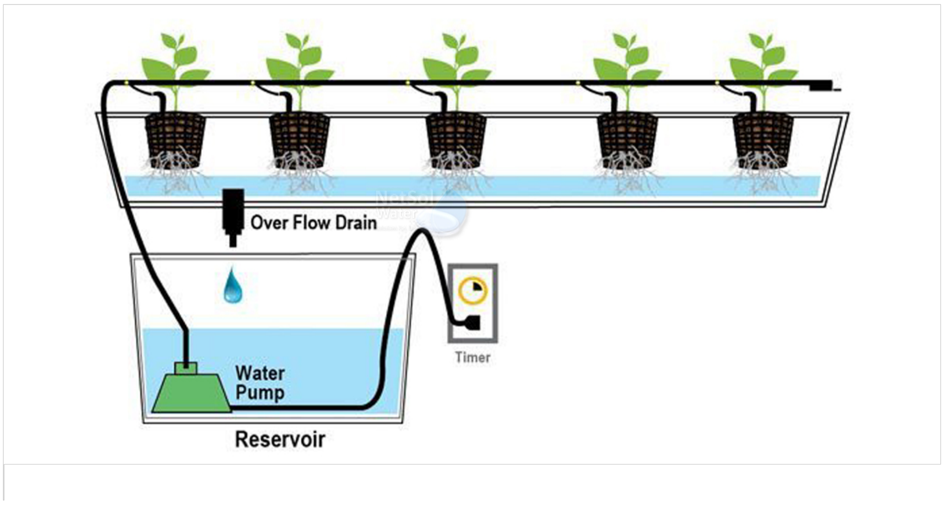

Figure 1.4: Hydroponic scheme [2.0]

the correct nutrient composition required by the crops.
Instead of soil, the hydroponic gardeners can use different types of solutions for what concern the mechanical support, such as coconut coir, vermiculite, perlite, and others. Therefore, the idea of this method is to remove the most barriers between the roots of the crop and the water, oxygen and nutrients necessary for the growth of the plant. In an open system the nutrient solution is provided to the plants once and the remaining solutions are drained. In closed system, the nutrient solution is reused and recycled. For this reason, the closed system is less impact to the environment. There are many different types hydroponic system, which are:

1. Ebb and Flow: in this system, after being seeded into sponge-like peat moss grow plugs, the growing plants are moved into horizontal trays, where they stay through the sprout and the seedling stage.
   During these weeks, the nutrient solutions mixed with water are provided at the crops on a regular schedule. The nutrient rich-water is transported to the trays, filling enough to saturate the roots. After that the water is pumped out or drained in a reservoir in order to be reused [2.1].

2. Drip Irrigation: this method uses the gravity to provide the drip irrigation to the crops. Into a main tank, the nutrient solutions are mixed with the water. The nutrient-rich water is, then, released through some drip emitters to the end of the plant on a regular schedule. This system contains a wicking material, which helps to move the nutrient-rich solution in the root's direction. Water

left unconsumed by the plants flows to bottom and then it is recirculated to the main tank [2.1].

3. Deep Water Culture (DWC): this type of cultivation is known also as lettuce raft method. Indeed, it is mostly used for light weight and small crops, such as herbs, basil, lettuce and spinach. This method consists in growing plants in rafts, which float in a highly oxygenated solution based on water and fertilizers [1.0].

4. Wick System: they are the most easy form of hydroponics, indeed they are an optimal introduction for beginners to start learning the basic principles of the hydroponic systems. Wick Systems are passive, so they do not contain moving parts. Usually, with this method the crops used are fast-growing, such as lettuce and herbs. In this system, the roots of the plants are always in contact with the nutrient-rich water, similar to the Deep Water Culture. The difference between the two methods is that in a Wick System there are two ore more wicks, which transport nutrient-rich solutions from the reservoir to the roots via capillarity action, while in DWC, the roots are directly submerged in the reservoir itself [2.2].

5. Nutrient Film Technique (NFT): this is a popular and versatile hydroponic method. This system is similar to Ebb and Flow, so there is a pump, which deliver the fertilizer water to the grow tray, and a drain pipe, which recycles the unused nutrient-rich solution. Differently from the Ebb and Flow method, in NFT the nutrient solution continuously flows over the roots, thanks to the gravity. For this reason, the grow tray is placed in a determined angle to allow the water to flow down to the drain pipe, and a new nutrient solution is continuously pumped into the high end of the tube.
   NFT is an active system because it needs to have moving parts in order to work. This system works at its best with crops that do not need a lot of support, so lightweight and fast-growing plants [2.3].

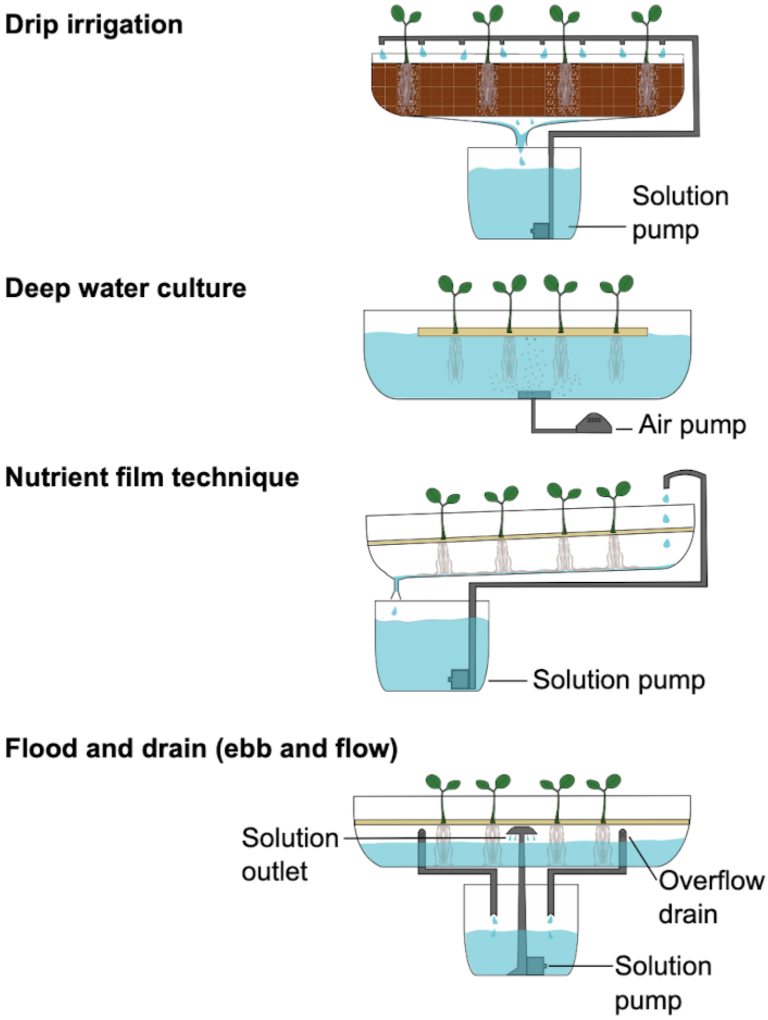

Figure 1.5: Different hydroponic systems [2.4]

1.3.2 Aeroponics

The word 'aeroponics' derives from the Greek 'aer', which means air, and 'ponos', which means labour. Indeed, this method consists in exposing plant roots to nutrient-containing aerosol droplets. It is a part of hydroponics system, in which the roots are stored or exposed continuously in an area filled with droplets (fine or aerosol) of mineral solution [3.9]. This system is the most efficient plant-growing system for vertical farms, using up to 90% less water compared to the most efficient hydroponic systems. It is also shown, that the plants grown in the aeroponic systems are able to uptake more minerals and vitamins, making the crops healthier and potentially more nutritious.

There are two different methods for the aeroponics: high pressure atomization and Aero-Hydro system, as shown in figure 1.6. The only difference is that in the second one, the lower root bed are exposed to the recirculated nutrient solution. In both cases, aeroponics atomized the nutrient-rich solution, which deposit onto the root surface.

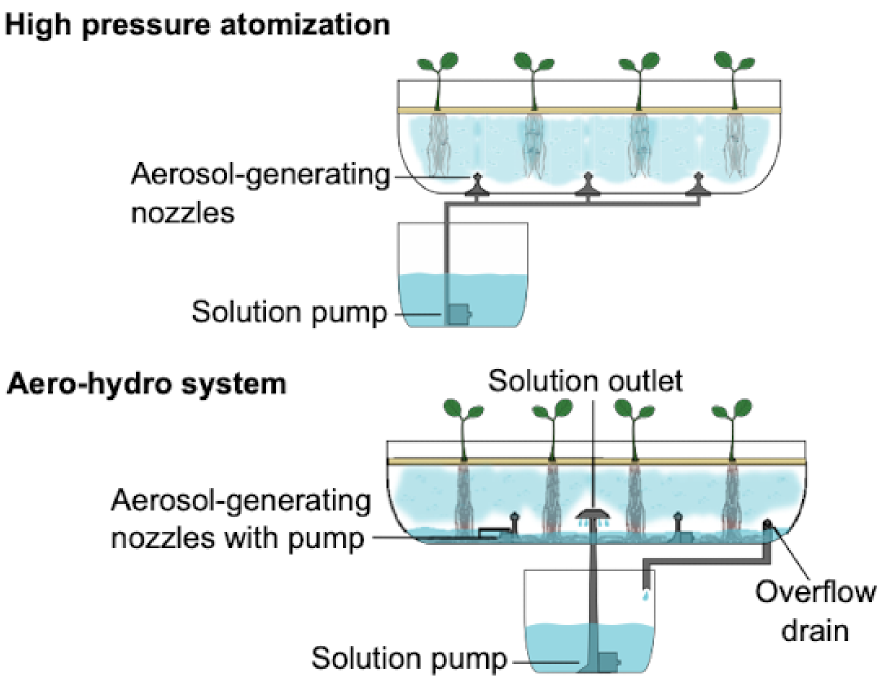

Figure 1.6: Different aeroponic systems [2.4]

The most commonly used is the high pressure atomization, where high pressure nutrient solutions are forced through a small orifice, breaking the liquids into droplets, which are about of 10-100 μm. There are also other methods of atomization, such as ink-jet printer droplet on-demand generators, low pressure atomization and ultrasonic atomization, that can generate varied droplet size distributions.

In the figure 1.7, it is shown the models for irrigation cycle and nutrient exchange during aeroponic horticulture, divided for three different phases: deposition, retention and decay. During the deposition stage, bigger aerosol droplets deposit onto the plant's roots surface, instead the smallest ones could access spaces between root hairs. Moreover, some droplets can also collide, increasing their volume and exit the aerosol, depositing on the roots surface or at the bottom of the bed into the nutrient solution. In the second phase, the retention, there is the accumulation of thin-films, usually heterogeneous, over areas of the root surface that remain for

a period of time. Because of heterogeneity of the films, also the gas exchange and the nutrient uptake vary. During the decay stage, the heterogeneous thin-films are removed by evaporation and gravity, which depend on the root architecture, the surface tension and the relative humidity. Then, the thin-films are integrated by the new ones from a further aerosol.
In the picture 1.7b, it is represented the model for nutrient uptake and gas exchange in an aeroponics system. When the droplets are deposited on the roots surface, the quantity of gas exchanged between the root and the environment will decrease and the availability of nutrient will increase.

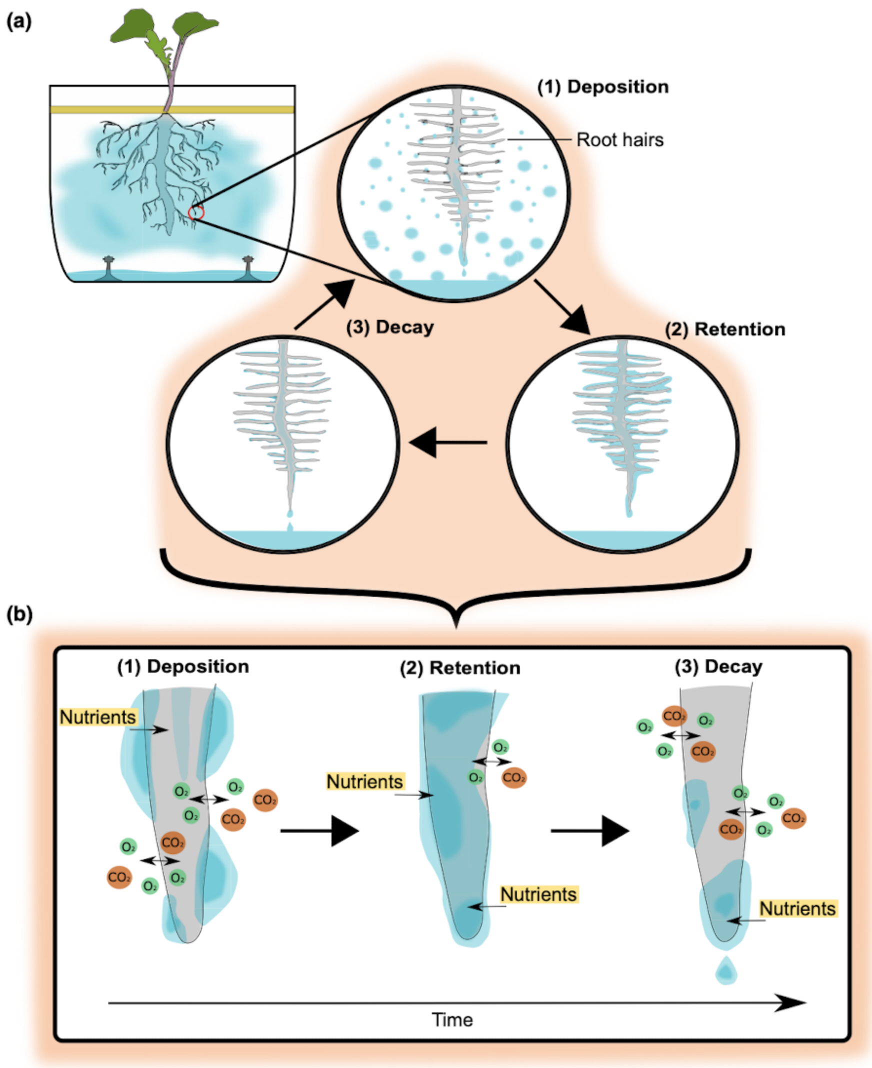

Figure 1.7: Models for irrigation cycle and nutrient exchange during aeroponic horticulture [2.4]

It was studied that the productivity in an aeroponic system can be higher for certain crops respect the traditional and the hydroponic cultivations. In the study reported in [2.5], the results showed that the yield of basil, parsley, cherry tomato, squash, bell pepper and red kale are increased, respectively,by 19%, 21%, 35%, 50%, 53% and 65% in an aeroponics cultivation compared to the soil culture.
Other study, [2.6], reported that the potato tuberization occurred 6-8 days earlier in an aeroponic system than in an hydroponic cultivation. However, a separate study, [2.7], resulted that the aeroponic cultivation, compared to an hydroponic system, increases potato mini-tuber yield by 70%, but the mean tuber weight was 33% lower.

In an aeroponic system, the roots can access all available root zone oxygen, while in the hydroponic cultivation, because of the low water solubility of oxygen, needs a continuous monitor of the dissolved oxygen concentration, especially for some types of species, in order to ensure that the plant growth is as efficient as possible. This can be achieved with a regular nutrient solution cycling, or by bubbling oxygen in the nutrient solution [2.4].

In figure 1.8a, it is shown the interactions between the environment and a plant, which is grown in an aeroponic system. The productivity of the plants is influenced by the light and dark conditions, by the temperature of the growing chamber, by the endogenous circadian rhythm, by nutrient supply cycles, by the concentration of the CO_2 and of the O_2 in the root zone. In a controlled-environment cultivation, it is possible to set these conditions, in order to optimize the plants growth and development. For example, since the light spectrum influences the morphology and the metabolite content, it is possible to alter the spectrum to adjust the shape, flavour, fragrance or nutrient content.
Moreover, the Volatile Organic Compounds (VOCs) released in the root zone could alter the aerosol properties and the nutrient availability. The interactions between root exudate compounds and nutrient solution ions will affect the development and the retention of the thin-film. The aeroponic microbial community is shaped by the root exudates, and the microbial exudates can affect the productivity and protection of the crop.
The anatomy and the architecture of the roots can be different depending the cultivation system considered. In an aeroponic cultivation, as shown in figure 1.8b, the roots shows plenty of root hair, which influences aerosol capture, and hydrophobic barriers in the exodermis (shown in red), compared with the hydroponic system.

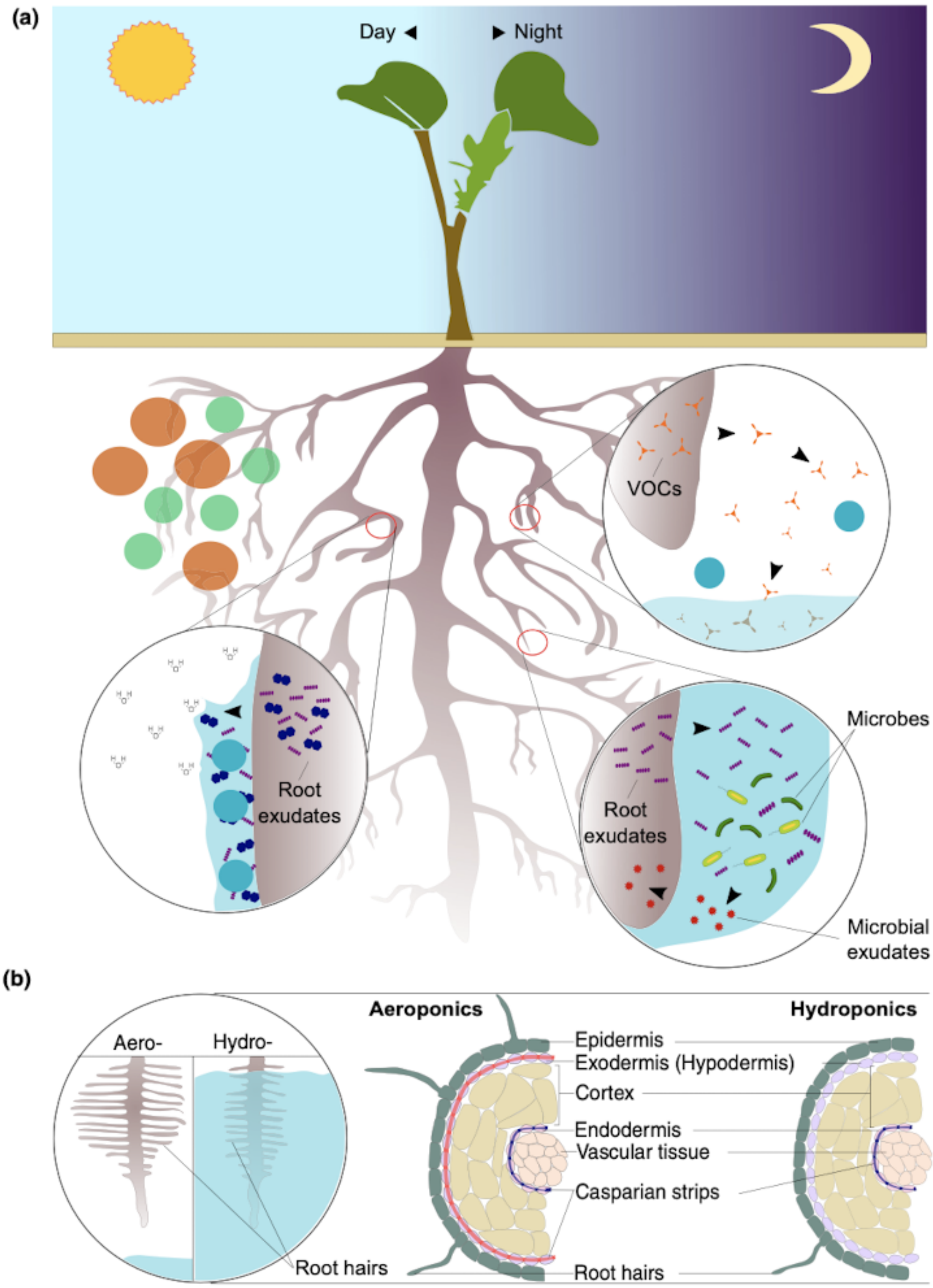

Figure 1.8: Interactions between plants grown in aeroponics system and their environment [2.4]

1.3.3 Aquaponics

Aquaponics is a technique characterized by the cultivation of plants and fish in a recirculating environment. Therefore, this method is a mixture between hydroponics and aquaculture, which is growing, breeding and harvesting of fish, as shown in figure 1.9. According to the Aquaponics Gardening Community definition, 'aquaponics is the cultivation of fish and plants together in a constructed recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrition. This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers' [2.8].
The input used in this system is the food for the fish. As food is eaten by the fish, they transform it into urine and fecal matter, both rich of ammonia. Thereafter, the ammonia-rich water, decay plant matter and the non-eaten foods flow from the fish tank to a bio-filter, in which the bacteria break everything into organic nutrient solutions, rich of nitrogen, for growing plants. The plants then filter the waste water that is recycled the fish ponds.

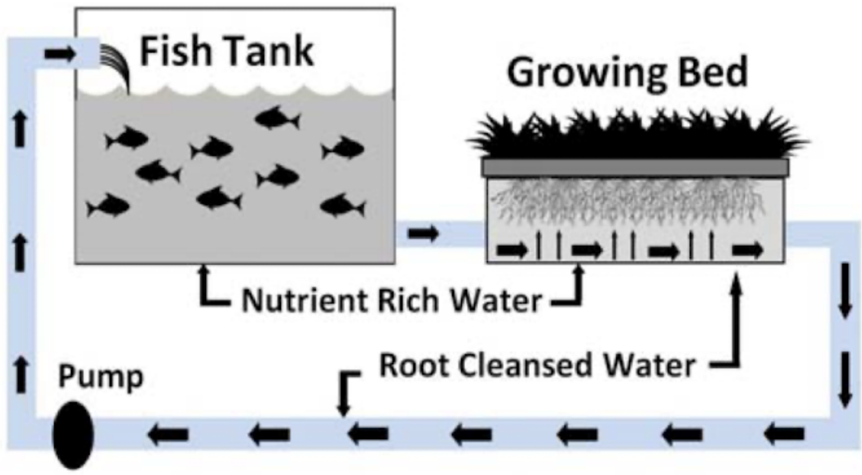

Figure 1.9: Aquaponics scheme [1.9]

In the study conducted by Thorarinsdottir, [2.8], it is specified that there are three different aquaponics systems: media beds, floating rafts or Deep Water Culture (DWC), and nutrient film technique (NFT). The media beds are characterized by various substrate in an 'Ebb and Flow' process, as described in 1.3.1, while in NFT and in DWC, the plant roots grow directly into a thin layer of water and into floating rafts in large water tanks, respectively.

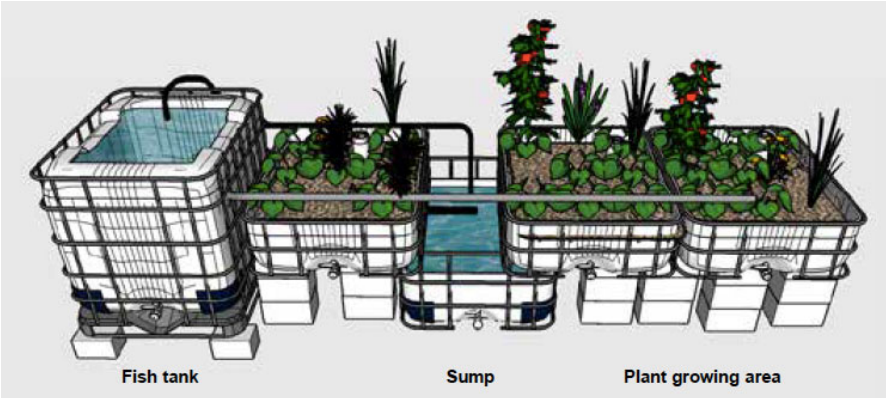

Figure 1.10: Media Bed scheme [2.9]

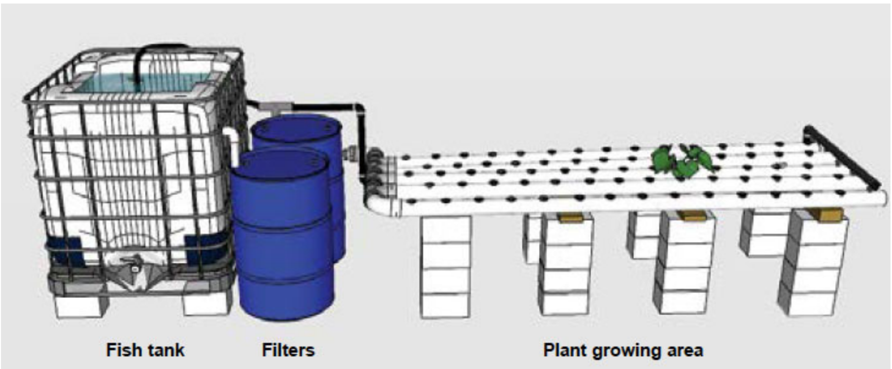

Figure 1.11: Nutrient Film Technique scheme [2.9]

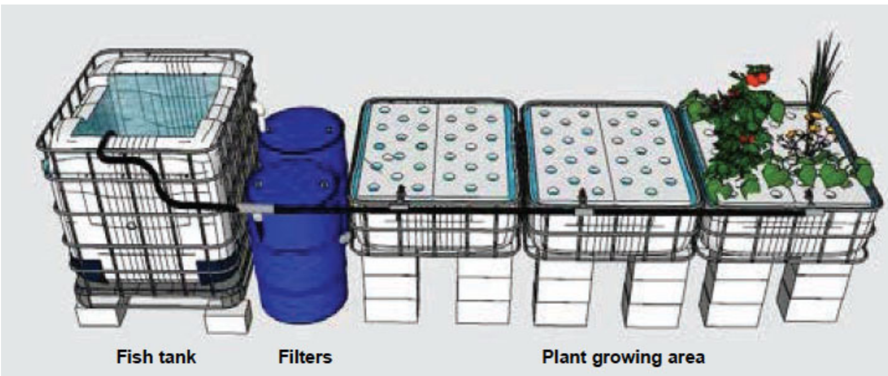

Figure 1.12: Deep Water Culture scheme [2.9]

1.4 Design setups of Vertical Farming

Vertical farming systems can be designed in very different ways, using for example existing buildings or rooftops. The setup can be divided into multi-level horizontal systems and vertical systems. The first one is shaped by the horizontal layers, which are stacked one above another and it is predominantly used for large-scale growing of one or many different species, such as lettuce or spinach. On the other hand, the vertical systems features high vertical planes. The main designs are the followings [1.0]:

- Reuse of buildings: in this system, the different horizontal layers are defined by the floors of the building taken in consideration, with different conditions present in each level. With this type of design, it is though to produce a large number of different species. Usually, this category includes historic buildings that are not used in modern cities. Parking areas or structures can also be used for this purpose. *The Plant* in Chicago is one example of vertical farming in existing buildings. This demonstrates how it is possible to transform waste in a resource, achieving economies of scale and incubating small businesses [3.0].

- Shipping containers: this design has the advantage that can be moved or relocated based on the density of urban areas. These containers contain staked shelves, LED lights, drip irrigation and they are digitally monitored. Examples of this system are *Crop Box* [3.1] and *Growtainers* [3.2].

- Rooftops: on the rooftops of the buildings, usually, there is enough space to design a vertical farm. This system has the advantage to use the sun light for the plant growth, instead of artificial lighting needed in the indoor methods. *Brooklyn Grange* is a firm which is the leading rooftop farming and intensive green roofing business in the US [3.3].

- Rotating Systems: it is characterized by horizontal plates which rotate so that each plate can reach top layer where direct sunlight is available. This system uses partially sunlight and partially artificial lights. *Sky Greens* patented its vertical farming system, which consist of rotating tiers of growing troughs mounted on an aluminium frame [3.4].

- Green Walls: this method consists in growing plants in areas like building facades. The plants can be positioned completely vertically or slightly inclined. It is important for this system to take in consideration in the design phase the light availability. The *Tree House* in Bukit Timah, Singapore, won the Guinness World Records with its two facades of vertical farming, which represents around 2289 square meters [3.5].

- Cylindrical Growth Units (CGU): usually, in CGU are cultivated various types of herbs, lettuce and strawberries. This system consists of cylindrical unit, in which are contained nutrient solutions like a hydroponic substrate.

- Cylindrical Rotatory Systems: this method consists of cylindrical units, in which the plants can rotate around a centre unit, in order to reach equal light at a particular time.

1.5 Growing substrate

In soil-less cultivation, the soil is substituted by organic or inorganic substrates. In this way, it is possible to reduce the water consumption as the water holding capacity of the substrates is higher than to the soil. Moreover, it is reusable year after year. The main characteristics, which should be taken in consideration when a growing media is chosen, are the Water Holding Capacity (WHC), Air Porosity and Density. Nowadays, the most common medium are perlite, rock wool, coco-coir, gravel, sand, pebbles, nutmegs, coco-pits, hydro-corn or grow rock, and clay balls. Each of them presents different characteristics, making better one substrate in some condition respect to another. For example, due to the perlite presents a porous nature, the plants roots have an healthy growth. Coco-pit is used, instead, to retain the wetness for a longer time than the other growing mediums. For this reason, it is becoming more popular. The growing mediums, which present an high water holding capacity, such as perlite, rock wool, coir pith, permit to reduce the irrigation cycles [3.9].

Nutrient concentrations need to be greater in production systems, which require fewer irrigation, in contrast with systems requiring more frequent irrigations. For every type of crop, it is necessary to select the appropriate growing media in order to avoid the clogging of irrigation. For instance, horticubes are often selected as growing media due to it characteristics, like easy to handle, sterile and stable pH. On the other hand, organic substrates, such as coco-pit, coir and husk, present their own chemical properties, which will influence the microbial richness, functions and suppress the effect on pathogens. One of the most important variable to take in consideration during the selection phase of the growing media for a specific crop is the moisture content. In table 1.1, some general characteristics of the growing medium are reported.

Table 1.1: General characteristics of growing media [3.9]

Growing Media	Overall porosity (%)	Aeration porosity (%)	Density ($g\ cm^{-3}$)
Rockwool	94	83.9	0.06
Coco coir Peat	92	79.8	0.16
Perlite	90	77.0	0.11
Sand	66	25.2	0.13

1.6 Nutrient solution

The major ingredient for the healthy growth of the plants in vertical farming is the nutrient solutions, which is composed by ions. They are obtained from the water soluble salts and they can be organic or inorganic solutions. The nutrient-rich water is composed by macronutrients and micronutrients. The first one are Nitrogen (N), Phosphorous (P) and Potassium (K), commonly called NPK solution. The micronutrients are usually Iron (Fe), Copper (Cu), Boron (B), Magnesium (Mg), Zinc (Zn) and Molybdenum (Mo). The other macronutrients, such as Carbon (C), Hydrogen (H) and Oxygen (O), are acquired from air and water [3.9].

In vertical farming, the knowledge of the plant is one of the most important aspect. Knowing the plant, it is possible to select the best nutrients for the growth of the plant and to optimize them in order to grow the nutritionally rich plants.
The plant growth can be affected by the different characteristics of the nutrient solutions and the quantity of ion concentration present in them. Moreover, the ion absorption by plant roots is determined by both root physiology and the mobility of ions in the solution itself, which, in turn, influences the plant growth, the crop yield and the product quality [3.6].
Some of the most important properties of the nutrient solutions are pH, temperature, ion concentration, electrical conductivity (EC), solubility, total dissolved salts (TDS). For example, for what concern the pH, the optimal range to grow healthy is 5.5-6.5 for the most of the plants. Instead, the electrical conductivity might be less than 2.5 dS m^{-1} [3.9].

The alteration of the quantity of the macronutrients and micronutrients in the nutrient solution, can cause deficiency and toxicity, producing effects on the plants. For example, high levels of nitrogen (N) can causes cracks in stem and distorts the leaves, which cause soft and blossom end rot. An excess of N can boost foliar growth and depress the growth of onion bulbs. Increased level of potassium (K) increases dry matter in the fruits. Phosphorous (P) causes the decreasing of the root growth, stems and reduce in uptake of other nutrients. For what concern the micronutrients, sulfur is responsible for uniform pale green chlorosis and pale green in veins. Instead, magnesium influences the yellowing between leaf veins, plus scorched and curling leaf edges and pulpy fruit [3.9].

1.7 Controlled Environment Agriculture (CEA)

In recent years, the Controlled Environment Agriculture (CEA) is becoming year after year more popular due to its advantage of growing any kind of plants in a controlled environment without the use of soil. Moreover, it allows to reduce the use of water and area to grow crops and it helps to provide the specific nutrient solutions for each type of plant. The soil-less agriculture permits to monitor the nutritional richness in the plants, maintaining the pH by adding or reducing the concentration of the nutrient solution. Additionally, it helps to reduce the problems that can occur in the traditional cultivation, such as pests and disease.

Soil-less cultivation is a growing sector, which could be helpful to the human being due to the increase in population and the little availability of land and natural resources, such as water. Smart farming can reduce the yield gap and can maximize the crops' production, using some emerging technologies, such as Internet of Things (IoT), Big data analytics and Machine Learning. Additionally, the crops, produced in a controlled environment, present a superior quality because of the absence of pesticides residues. The major advantage of the smart farming is that it is possible to use precise amount of nutrient solution for each type of plant, in order to reduce the use of pesticides resulting in high nutrient use efficiency. Moreover, in these advanced soil-less cultivation methods the labour force required to do all the intercultural operations, such as fertilizer application, weeding and earthing up, is not needed, in contrast with the traditional agriculture. Many activities can be automated thanks to the interactions between IoT and Artificial Intelligence (AI), such as machine learning algorithms, deep neural network techniques and Fuzzy logic.
Some of the activities involved in automation of soil-less agriculture by using smart sensors and IoT technology are shown in 1.13.

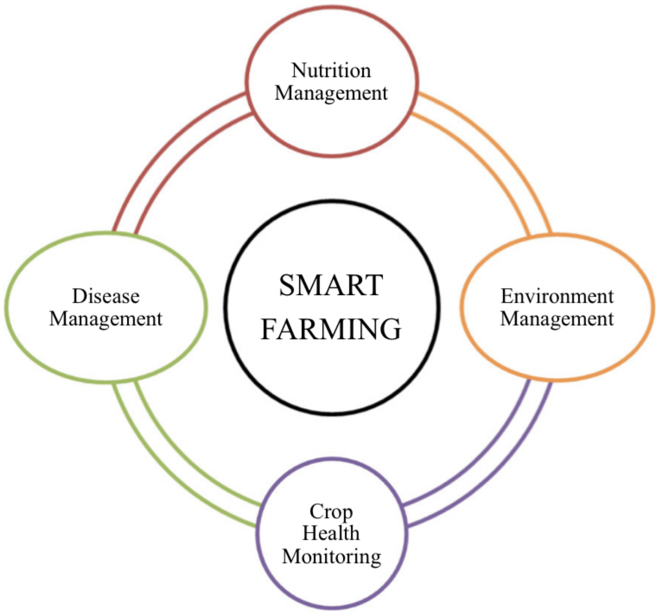

Figure 1.13: Process involved in automation of soil-less agriculture by using smart sensors and IoT technology [3.9]

Nowadays, there are new technologies and many sensors, which are employed in real time monitoring of the systems, in order to collect a large number of data flows to analyze in order to maximize the efficiency on the use of the nutrient solutions. Machine learning algorithms, as neural networks and genetic algorithms, are a useful resource to self-analyze and calibrate nutrient solution parameters based on sensors data. It is possible to forecast the quantity and the quality of the vegetables or fruits production under different conditions through simulation techniques and advanced big data analytics. These Artificial Intelligence (AI) techniques and Internet of Things (IoT) help to create a real/physical system in order to monitor the parameters, such as the composition and the concentration of the nutrient solutions and, at last, they help to achieve an higher crop productivity.

The Internet of Things (IoT) is a distributed and interlinked structure of embedded systems interacting through wireless and wired technologies [3.9]. Currently, IoT is playing a key role in the world because it permits energy automation for improving the quality of life. The Wireless Sensor Networks (WSNs) are networks in which the information is collected from many different sensors characterized by a wide level of communication. WSNs includes several sensor nodes, which are able to monitor different parameters, as moisture, humidity, temperature and many others. In this way, it is possible to monitor these parameters in order to facilitate precision agriculture, which permits to reduce water consumption, fertilizers usage and energy savings. The most important component in the WSNs node is the microcontroller, which is employed to process the data acquired by the sensors. The application of IoT in the agriculture sector is in an early stage, therefore there is still space for improvement and development of these systems.

1.7.1 Smart sensors

As previously mentioned, the smart sensors are important tools, which help collecting data from the systems in order to achieve precision agriculture. Year after year, the number of smart sensors available in the market is constantly increasing, and their usage has tripled since 2016. The most common sensors used for CEA are pH sensor, temperature and humidity sensor, water level sensor and electrical conductivity sensor. Lately also other sensors, such as ion selective electrode sensors, leaf temperature sensors, dissolved oxygen/carbon dioxide sensors and imaging sensors, are being employed in hydroponics, aeroponics and aquaponics systems [3.9].

Temperature sensors

The temperature sensor is one of the most used sensor in vertical farming due to the key role that the temperature has in the plant growth. Each species of plant has specific temperature requirements, which can be satisfied monitoring the value through the sensor [3.7]. The sensor can be used for monitoring both ambient and water temperature [1.1]. If the temperature exceeds the determined value, a fan present in the environment should be turned on and switched off when the temperature is in the threshold required for the plant [1.0]. The temperature measuring range is 0-50 °C with an accuracy of $\pm$ 2% and an operating voltage between 3.3 and 5.5V [3.9].

Humidity sensors

The humidity presents in the air in the vertical farming has to be monitored because a proper level of moisture is crucial for the plant growth, because it affects the rate of transpiration, which is the process with which the plants take water and nutrients [3.7]. The humidity range that can be measured with the sensor is 20-90%. It is possible to notice the change in the humidity when the resistance between the electrodes changes [3.9].

CO_2 sensors

The level of the carbon dioxide (CO_2) in the growing environment an impacting factor in the development of the plants, because it is one of the primary sources used by the plants to produce glucose through photosynthesis. In a controlled-environment agriculture, it is important to monitor through a sensor the quantity of CO_2 present in order to optimize the growth characteristics of the plants and the crop yield. Moreover, the presence of the carbon dioxide can be used as pest control tool [3.7].

pH sensors

The pH of the nutrient solution is an important parameter which strongly influences the growth of the plants. For this reason, it should be monitored continuously. The pH of the solution give a detail of the acidic and the basic nature of the fertigation water. The optimum range of pH maintained in the plant production is 5.5-6.5. If the value collected by the sensor is outside of these thresholds, the nutrient uptake could be affected, compromising the growth of the plants. The sensors report if it is necessary to add or to reduce the chemical concentrations in the nutrient solutions [3.9].

Electrical Conductivity (EC) sensors

The Electrical Conductivity (EC) measures the total concentration of the salts in the nutrient solution, which influences the ability of the plant to absorb water. It calculates the amount of salinity present in the solution, which should be maintained between 1.5 and 2.5 dS m^{-1}. Moreover, it is a indicator of water quality and fertilizer concentration. EC levels can help plant production and lead to more cost-effective use of plants inputs and less shrinkage [3.9].

Ion Selective sensors

The Ion Selective Electrodes (ISE) and the Ion Selective Field Effect Transistor (ISFET) are used to measure the individual ion activity in the nutrient solution and not the concentration of the solution, which is measured by EC sensors. The concept of the ISE sensor is to create an electrical potential equivalent to the activity of specific ions dissolved in the solution. In this way, ISE sensors can measure the cations and the anions activity in the roots and its surrounding environment. These sensors provides a good knowledge of the ecology and biology of the plants and they help to reduce the use of fertilizers solution [3.9].

Leaf temperature sensors

The use of a leaf temperature sensors is useful to understand the number of cycles of irrigation needed by the plants based on site-specific location, they provide the health status of the plants, they identify pathogen stress in the plants before it is actually visible and they analyze nutrient deficiency. There are four different types of leaf temperature sensors: thermal resistant, thermal sensor, infra-red temperature measurement and infra-red thermal imaging temperature measurement. The last two types are used typically for sensitive leaves, such as lettuce and geranium. However, these methods, through an implementation, can also be used on other species like tomato, cucumber and basil helping to understand any type of stress related to water in order to improve the productivity [3.9].

Dielectric sensors

In soil-less farming, as described in chapter 1.5, in order to grow the plants, it is necessary the use of growing medium. Each of them presents different characteristics, but one of the most important to be considered is the moisture content, which determines the uptake of water by the roots of the plants. The knowledge of this variable is necessary because it influences the irrigation cycles, the quantity of fertilizers and the time taken for harvesting. The sensor used to measure the moisture content is the dielectric one. It monitors the water content of the medium by determining its dielectric properties or change in weight of the substrate. The basic principle of the dielectric sensor is the growing medium acts as the dielectric material with the two electrodes placed between them. The corresponding electric voltage and the dielectric properties provides the specific ion conductivity and that is correlated with the moisture content of the medium used [3.9].

Dissolved Oxygen sensors

A vital role in the growth of the plant is played by the Dissolved Oxygen (DO) present in the irrigation. In hydroponics, the plant roots should be supplied with the optimal amount of oxygen in order to reduce the cropping time. Temperature of fertigation water also influences the amount of DO present in the water. Temperature above 35 °C reduces the leaf water content and induce some disorders in the plants root system. Consequently, higher the temperature, lower the dissolved oxygen in hydroponic solution followed by decreased respiration rate in the root system. If the dissolved oxygen has a value below 3 or 4 mg L^{-1}, it inhibits the growth of the roots and produces changes to brown, which can be considered as a first symptom of the oxygen lack [3.9].

Imaging sensors

The imaging sensors are really helpful to detect disease/pathogens in the plants, to find deficiency/toxicity of nutrients and to identify the different types of plants in real time. Optical sensors are employed for the primary identification of disease focal points in the plots and areas varying in the severity of diseases in the plant production factories. In agriculture there are many different imaging sensors which could be used, such as RGB (Red-Green-Blue) imaging sensors, spectral imaging sensors, thermal imaging sensors and fluorescent imaging sensors [3.9].

Light intensity sensors

In soil-less cultivation, the plants can be exposed to the sunlight, but frequently they need artificial lighting, which promotes the effective growth of the plants. In Vertical Farming it is always necessary the use of the LED due to the presence of different levels of cultivation, instead the soil-less cultivation in greenhouses can use both artificial lighting and sun lighting. In order to maximize the economic benefit of yielding high quantity and quality of plants it is necessary to monitor that the light intensity is included in the optimal range. As a matter of fact, the light intensity influences the photosynthetic behaviour, antioxidants capacity and physiological characteristics of the plants [3.9].

1.8 Light's impacts

As mentioned previously, in the indoor cultivation the artificial light plays an important role because it is essential for the plants growth. Nowadays, the artificial lighting is composed by the Light Emitting Diode (LEDs). The rapid evolution of the LED lighting technologies experienced in the last decade has revolutionized the cultivation in the greenhouse and in controlled-environments, such as vertical farming. Compared to the traditional lighting used in the agriculture, the LED are preferred because they can manipulate how plants are growing to some extents. This is possible thanks to the availability to select the specific desired wavelengths, which are needed in order to obtain the desired result [1.0].

A Light Emitting Diode (LED) is a semiconductor device, which can emit light when an electric current passes through it. The electrons present in the semiconductor recombine with the electron holes, releasing energy in form of photons. The energy of the photons correspond to the color of the light emitted. This is determined by the energy required for electrons to pass over the semiconductor's band gap, which is an energy range in a solid where no electronic states exist. By using multiple semiconductors or a layer of light-emitting phosphor on the

semiconductor device it is possible to obtain the white light.
The use of LEDs compared to other types of artificial lighting is preferred because they present numerous advantages, as:

- lower power consumption;
- longer lifetime;
- high radiant efficiency;
- improved physical robustness;
- smaller size;
- faster switching;
- high capacity to regulate the luminous emissions in term of spectral composition, matching the plant's need and allowing for high quality crops.

On the other hand, the most impacting disadvantage of the LEDs is the initial cost, which is higher compared to other horticultural lighting typologies, despite in the last years the price has decreased remarkably.
Natural sunlight contains a wide continuum of wavelengths and fluence and is optimal for plants. However, it is essential to manipulate the light conditions of artificial light sources in order to grow plants in vertical farming obtaining electrical cost savings and balancing the yield and quality of plants. It was studied that the various regions of the light spectra have different efficiencies in enhancing the plant photosynthetic process and plant morphological, physiological and biochemical responses. Moreover, eliminating the production of the other wavelengths, which are not useful for the growth of the plant, is possible to reduce the energy costs by as much as 15%.

The plants can absorb and utilize only certain spectrum of light. In particular, the light available for photosynthesis is called Photosynthetically Active Radiation (PAR) and includes wavelengths from 400-700nm. Consequently, the light produced outside this range cannot be absorbed by the plants. The PPFD (Photosynthetic Photon Flux Density) is used to measure the amount of PAR that is actually reaching the plant at a specific location and time. It indicates the numbers of photosynthetic active photons hitting a surface per second; its unit of measure is μmol/(m^2s). Therefore, the PAR is the type of light, instead the PPFD is the quantity of light. Moreover, within the visible light spectral range, different wavelengths of light can trigger different responses in the plants [4.2]. The Photosynthetic Photon Efficacy (PPE) is a measure of how efficiently plants convert light into useful chemical energy. The higher the PPE, the more efficient the plant is at converting light into growth. The recent advances in LED technologies have

increased the PPE up to 2.3 μmol J^{-1} [4.3]. The red (R) and the blue (B) light is the main focus of researchers, because it has been found that these two different wavelengths have an important impact on the growth of the plant. It is necessary to define the optimal combination ratios of the red and the blue light because their wavelengths are close to the absorbance of photosynthetic pigments that effectively drive photosynthesis.
During the vegetative stage, increasing the amount of blue light (400-500nm) can result in more compact and stockier plants, which creates a more even canopy height and ensure that plants receive equal amount of light. Furthermore, the blue light has effect in chlorophyll production, stomata opening and photosynthesis.
The red light (600-700nm) contributes to photosynthesis and has effect on the plants morphology, such as increased biomass accumulation, stem elongation and leaf expansion. These effects are more impacting in the flowering and blooming stages of the plants growth because the growth rate of the plant increases, resulting in larger yields. Moreover, it is particularly useful as it is the most efficient light to produce using LEDs, getting the most light per watt of power used [3.8].

There are numerous researches in which there is only the use of monochromatic R or B LEDs and combined RB LEDs and the results report that the plants normally appear purplish-grey to the human eye, which leads to difficulties in the visual assessment of plant health. For this reason, it is possible to add the green (G) light, which present a wavelengths between 500 and 600nm. The G light has little impact on the plant photosynthesis and photomorphogenesis, but it has great ability to penetrate the folder layers of leaves and the lower canopy, which can increase photosynthesis in the lower parts of leaves as well as carbon assimilation. However, the use of the G LED light is not widely used due to the inefficiency in converting the electricity into photons. Alternatively, it is possible to apply the white (W) light, which include green light. Advanced LED technology enables broad-spectrum W LED light that consists of red, green and blue lights. In vertical farming, this could be effective to improve the growth of the plants and provide the desirable lighting for human vision [3.8].

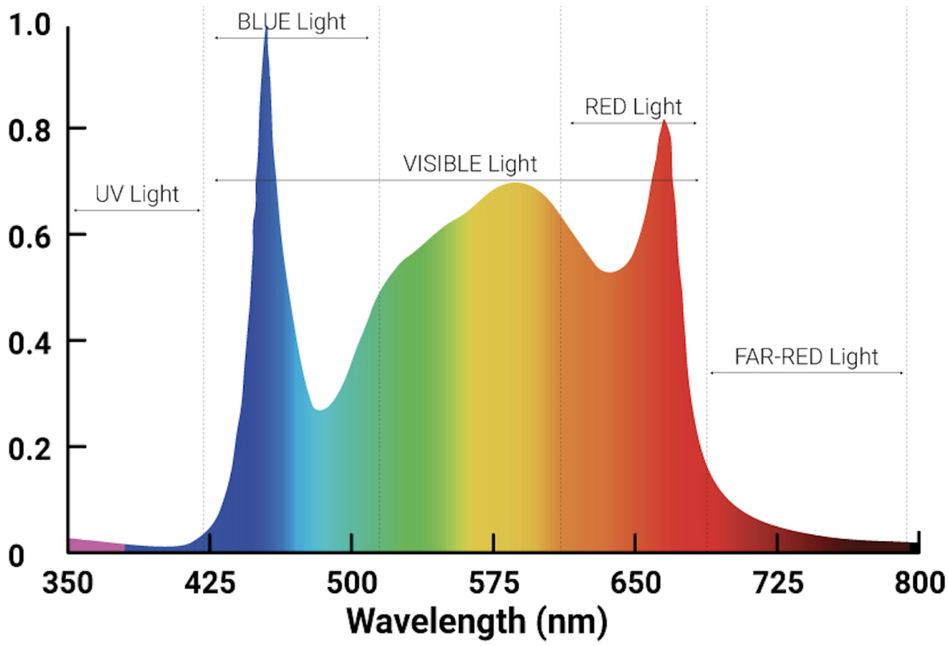

Figure 1.14: Spectrum of light [4.0]

In figure 2.3, are reported the UV light and the FAR-RED light. The first one does not contribute to the photosynthesis and it is still under research. However, the UV light has been shown in studies to increase terpenes and anthocyanins, which affect the color profile, aroma, and flavor of the plant's flowers. For what concern the FAR-RED light, it was not considered for a long time, but it is found that this section of spectra can have immense benefits for the plant growth. It can contribute to the photosynthesis and to increase leaf size, which, consequently, can increase the ability of the plant to absorb the light [4.0].

1.8.1 Analysis of experiments in literature

The light, as mentioned above, is one of the most important factor of the research. In literature, there are numerous experiments performed changing the combination of the LED light or the intensity. In order to find the articles related to the role of the light in vertical farming, a number of searches were conducted with different keywords on the website *Scopus* [4.1]. During the research, different query has been inserted to find the articles of interests. Some of them have been: 'vertical farming led effect', 'light effect vertical farming', 'vertical farming led' and 'vertical farming light'. For each of them, a different number of documents result has been obtained, and respectively they were: 68, 96, 168 and 247 articles for these keywords. The majority of these articles comprehends experiment conducted with different light

intensity on different species of plants. In order to evaluate the articles which were the most relevant for the scope, it has been conducted a selection by reading carefully the title, the abstract and the conclusions. In particular the selected articles are the ones which presents conditions and characteristics in common to the experiment to be performed, which helped to decide how to conduct the experiment. For example, more importance is given to the articles in which there are experiment on lettuce.
In this section, two of the selected articles have been chosen to be analysed because they present important foundations for defining the experiment to be conducted, as the PPFD used.

In [3.8], the experiment, conducted at Gyeongsang National University, consisted to analyze the growth of butterhead lettuce and romaine lettuce in an hydroponic system with four different LED sources: one combined RB LEDs and three different W LEDs light (NWL, SWL1 and SWL2), as shown in figure 1.15. The cultivation room, in which the plants were located, has some specific conditions: 25 °C, 150±5 μmol m^{-2} s^{-1} Photosynthetic Photon Flux Density (PPFD). During the first stage, the sowing one, the photoperiod was of 2 h for 11 days. After that, the seedlings were transplanted into a deep flow technique with a plastic container. The growing conditions were maintained at 20±3.0 °C air temperature and 80±2% relative humidity. Nutrient solution, characterized by a pH of 6.0 and an EC of 1.25dS m^{-1}, was used for the growth of the plants and was periodically replaced.

Light Source	Range (nm)	Peak Wavelength (nm)	Ratio (%)
RB	Blue (400–500)	444	47
	Green (500–600)	-	2
	Red (600–700)	665	51
NWL	Blue (400–500)	453	21
	Green (500–600)	586	42
	Red (600–700)	665	37
SWL1	Blue (400–500)	437	26
	Green (500–600)	526	41
	Red (600–700)	665	33
SWL2	Blue (400–500)	437	19
	Green (500–600)	578	43
	Red (600–700)	664	38

Figure 1.15: Spectral distribution of the four different LEDs sources [3.8]

The research was composed by two different experiments: one with constant electrical power and the second with constant PPFD. The results were analyzed after four weeks. In the figure 1.16, all the values for the two experiments are reported.

Experiment	Light Source	PPFD (µmol m^{-2} s^{-1})	Electrical Power (W)
Experiment 1	RB	129.73	80
	NWL	161.15	
	SWL1	172.28	
	SWL2	167.55	
Experiment 2	RB	147.50 ± 2.89	88.59
	NWL		63.10
	SWL1		65.01
	SWL2		59.24

Figure 1.16: Electrical power and PPFD for each LEDs sources used in the two experiments [3.8]

The results about growth characteristics of the first experiment, conducted with constant electrical power, underline the following aspects:

- the shoot fresh weight of butterhead lettuce in the SWL1 and SWL2 treatments is about 1.4 and 1.7 higher than the dimension in the RB-treated plants. In contrast, for what concern the romaine lettuce, the shoot fresh weight is enhanced by 37% in all the W treatments, compared to the RB treatment;
- the highest shoot dry weight is achieved in the SWL2 treatment for the butterhead lettuce. There are not significant differences in the romaine lettuce growth;
- the root fresh weight is not influenced by the different light sources for both lettuce types. The butterhead's root dry weight is slightly lower in the NWL and SWL1 treatments; whereas in the romaine lettuce, root dry weight is slightly decreased in all W treated-plants;
- compared to the RB light source, the leaf area and the number of leaf in the butterhead's crops are, respectively, around 80% and 28% higher in the SWL2 treated-plants. In contrast, in all W treatments, the specific leaf weight is lowered. The romaine lettuce is not influenced by the W treatments for the leaf number, the leaf area and the specific leaf weight.

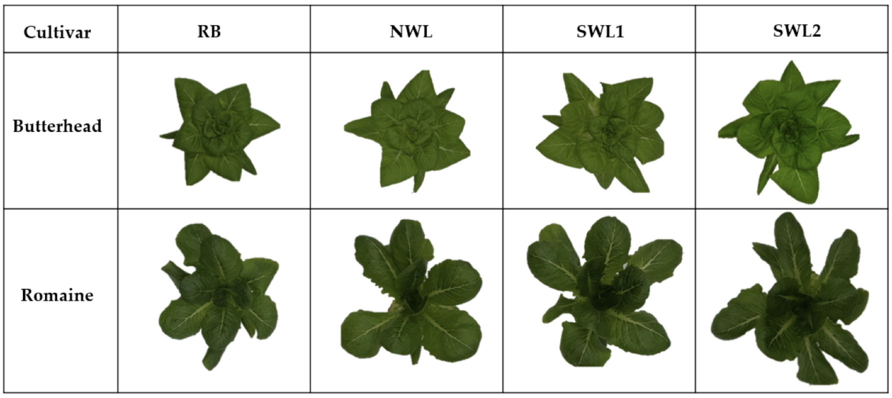

Figure 1.17: Experiment 1 - Growth characteristics [3.8]

For what concern the light and energy use efficiency, the results shows that the relative electric current is increase by 24-31% for all W treatments to provide the same electrical power of 80W as in the RB treatment. Furthermore, the PPFD of the three W treatments is increased by 1.2-1.3 times respect to the one of the RB treated-plants.
The figure 1.20A shows the values of different parameter for butterhead lettuce. It can be noticed that the Light Use Efficiency (LUE) has the maximum value in SWL2. The NWL treatment present a lower value compared to the RB treatment, instead the SWL1 a slightly higher value. The SWL2 treatment has the highest value of Energy Use Efficiency (EUE).
For what concern romaine lettuce, as shown in figure 1.20B, both LUE and EUE are slightly increased in all W treatments compared to the RB treatment.

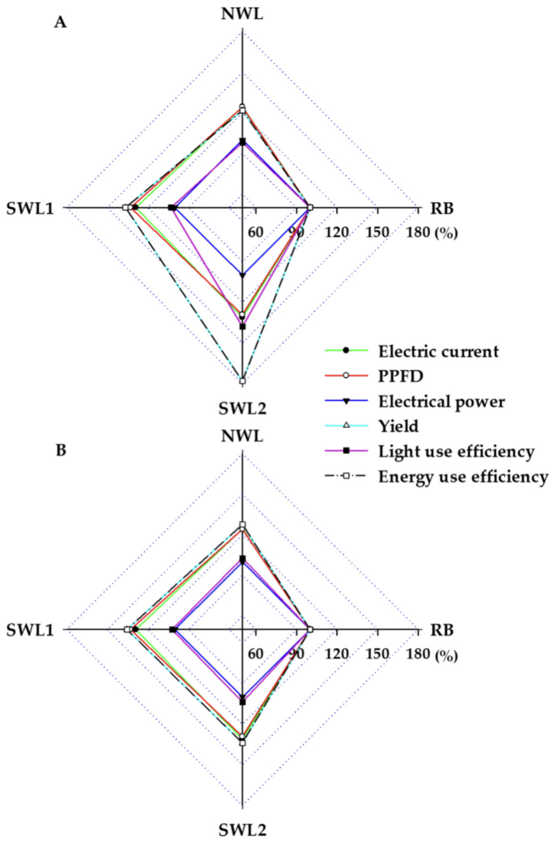

Figure 1.18: Experiment 1 - Light and Energy Use Efficiency [3.8]

The second experiment, conducted with constant PPFD, resulted in significantly consequences in the growth characteristics of the butterhead and the romaine lettuce. The main aspects are the followings:

- in the butterhead, the shoot fresh and dry weights in the SWL2 treatment are respectively 1.2 and 1.4 times higher compared to those of the RB-treated plants. For romaine lettuce, the value of the shoot fresh weight is the highest in the SWL1 treatment. Whereas, the shoot dry weight in SWL1 and SWL2 treatments is not so different from the RB treated-plants;

- there are no significant differences root fresh weight for both species of lettuce. The root dry weight SWL1 treated-butterhead is 1.6 times greater than in the RB treatments, differently from the romaine, in which there are not differences.

- for butterhead lettuce, the leaf area increases in all W treatments, the leaf number is not influenced by the different light sources, instead the specific leaf weight is lower in NWL and SWL1 treatments. In the romaine, in SWL1 treatment the leaf area is higher than in the RB treated-plants, there are no differences in leaf number and in specific leaf weight.

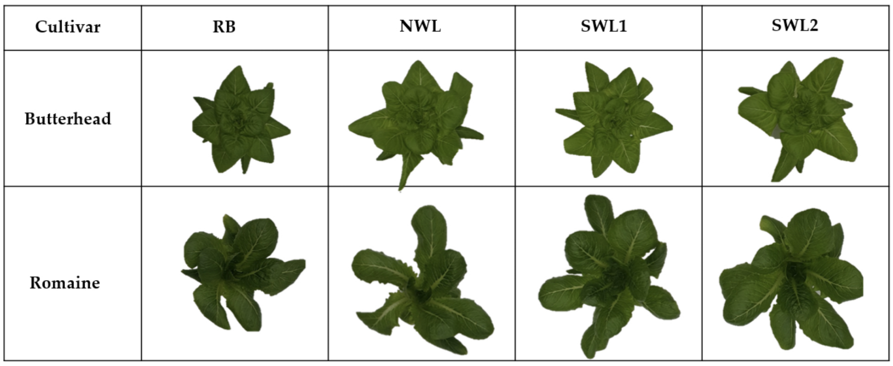

Figure 1.19: Experiment 2 - Growth characteristics [3.8]

To provide the same PPFD in all treatments, the electric current used in all W treatments is slightly decreased, and the electricity used in all W treatments is also reduced by 29-34% respect to the RB treatments. For both lettuce's species, the LUE is higher in SWL1 and SWL2 treatments than the other light sources. For what regard the EUE, in the butterhead lettuce the value is increased by 45-77% in all W treatments, instead in the romaine lettuce is increased by 38-85% than in the RB treated-plants.

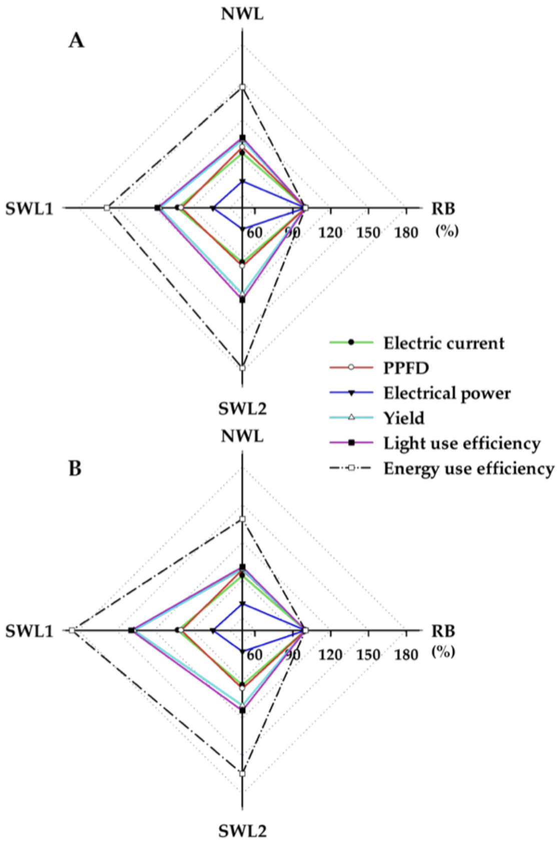

Figure 1.20: Experiment 2 - Light and Energy Use Efficiency [3.8]

The second document analyzed, [4.3], performed at the University of Bologna, aims to assess the eco-efficiency and food potential production of four different horticultural species (lettuce, chicory, basil and rocket) with different RB ratio in an hydroponic system. The growth chamber was set at 24±2 °C, 215±5 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD), relative humidity of 55-70% and the concentration of CO_2 of 450ppm. The photoperiod provided was 16/8 light/dark.
After seedlings were germinated, they are transplanted into an individual hydroponic systems, at different timing: after 14 days from sowing for lettuce, rocket and chicory, and after 21 days for basil. Lights treatments were differentiated with the five different RB ratio: 0.5, 1, 2, 3 and 4. The harvest was conducted for the lettuce after 14 days from the transplanting, and for the other species after 18 days. The experiment was repeated twice. In figure 1.21, all the date of sowing, transplanting and harvesting are reported for each species. The nutrient solution provided to the plants had a pH of 6.4 and an EC equal to 1.56dS m^{-1}.

Growing Cycle	Species	Sowing	Transplanting	Harvesting
1	Lettuce	28/02/2018	14/03/2018	28/03/2018
	Basil	01/02/2018	22/02/2018	12/03/2018
	Rocket	04/06/2018	18/06/2018	02/07/2018
	Chicory	25/06/2018	09/07/2018	23/07/2018
2	Lettuce	16/03/2018	30/03/2018	13/04/2018
	Basil	16/04/2018	07/05/2018	28/05/2018
	Rocket	10/09/2018	24/09/2018	08/10/2018
	Chicory	01/10/2018	15/10/2018	29/10/2018

Figure 1.21: Date of sowing, transplanting and harvesting for the four species [4.3]

The different light treatments causes differences in crop yield, electricity consumption and nutrient solution uptake, as shown in figure 1.22.

Crop	RB Ratio	Crop Yield (kg m^{-2} year^{-1})		Electricity Consumption (kWh·kg^{-1})		Nutrient Solution Uptake (L kg^{-1})	
Lettuce	0.5	48.7	d	25.5	a	21.3	a
	1	61.6	c	21.9	b	16.9	b
	2	79.4	b	20.3	b	16.4	b
	3	103.6	a	14.8	d	12.9	c
	4	86.4	b	18.1	c	15.4	b
Basil	0.5	32.3	b	48.5	a	29.6	a
	1	34.3	b	50.6	a	26.2	b
	2	56.1	a	34.0	b	22.7	c
	3	55.0	a	36.4	b	23.3	c
	4	53.0	a	39.5	b	25.2	bc
Rocket	0.5	34.6	b	47.3	a	55.6	a
	1	34.8	b	48.5	a	51.6	a
	2	51.6	a	36.5	b	38.3	b
	3	50.4	a	39.7	b	43.5	b
	4	54.9	a	35.8	b	38.8	b
Chicory	0.5	25.8	b	61.5	-	49.6	a
	1	27.0	b	63.0	-	47.5	a
	2	35.8	a	53.4	-	40.8	b
	3	38.8	a	53.8	-	39.4	b
	4	36.6	a	54.8	-	39.4	b

Figure 1.22: Crop yield, electricity consumption and nutrient solution uptake for the four species [4.3]

From the figure 1.22, it is possible to notice that the higher fresh biomass production for the lettuce is in RB3, instead for the other crops is for RB $\geq$ 2. For what concern the nutrient uptake, the higher values are when RB $\geq$ 2, except for chicory, in which there are not changes in daily nutrient solution uptake attributable to different light treatments. Due to the various RB ratio, the electricity consumption required to produce 1kg of crops yield changes. The lowest value obtained is associated to the production of 1kg of lettuce when RB is equal to 3 and it is 14.8kWh kg^{-1}. A similar trend is showed also for basil and rocket, in

which the highest values of electricity needed are associated to a greater fraction of blue light in the spectrum, so when RB ≤ 1, instead lower values are linked to the prevalently use of red light, so when RB > 1. The light treatments do not influence the electricity consumption for the chicory.
From an environmental point of view, the most impacting LED treatment is RB1 for the chicory, and the least impacting is the production of lettuce in RB3.
Although RB0.5 is the treatment which requires the lowest electricity, its crop yield production is lower than other treatments resulting in poorer performance when evaluating the environmental impact and economic cost per kg of product.

Chapter 2

The firm

Technophylla srl is a start-up born in 2022 in Turin with the aim to sustain the digital development in the agricultural sector, providing new products and services for the monitoring and for the remote diagnostic of production, collection, tracking, processing and distribution processes [4.4].
This firm is a spin-off of the company *Orchestra srl*, which provides technologies to be applied on machines and production plants in such a way as to bring the Industry 4.0 to more different situations. The two firms think products which can be used both in indoor and in outdoor locations.

Figure 2.1: Technophylla srl Logo [4.5]

2.1 SMARTFarming4.0

SMARTFarming4.0 is the IoT solution designed and supplied by *Technophylla srl* for the agribusiness sector. This product is used in order to plan, monitor and control the productive assets and to guarantee the traceability of products throughout the supply chain both for greenhouses and vertical farming and for traditional open field crops. SMARTFarming4.0 is a web-app installed in the company server, which is connected to a network of production units, sensors and actuators to monitor and trace the operations in real time. Moreover, it collects all the data in order to follow the growth and the work done. In this way, it is possible to understand what are the improvements that can be done. The precision farming in open fields and in soil-less cultivation is granted by the cloud driven edge computing that this solution provides [4.5].

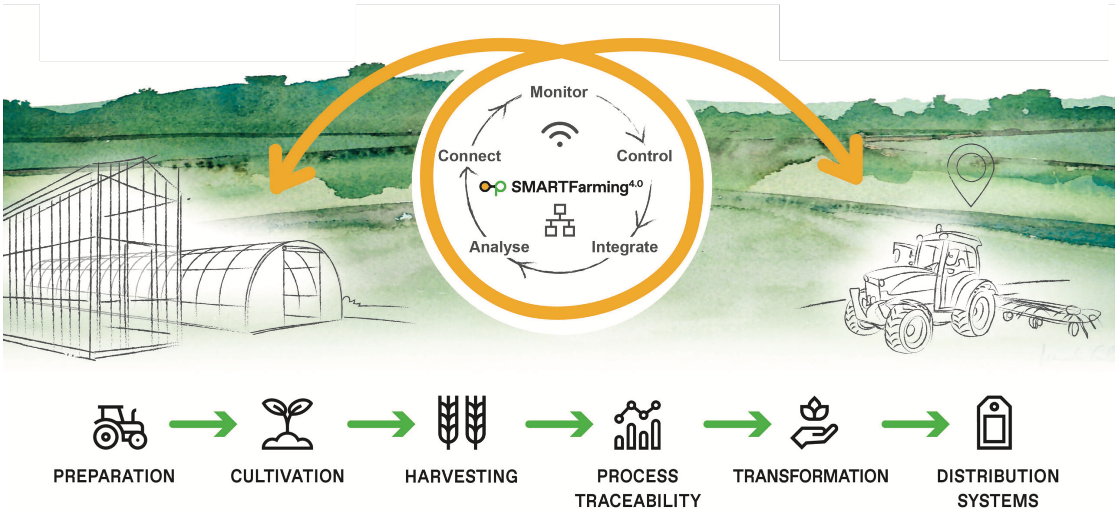

Figure 2.2: SMARTFarming4.0 [4.5]

The version of SMARTFarming4.0 for the indoor cultivation has to plan and monitor in real time the development of the production. Moreover, it has to control the environmental condition in order to ensure lush growth and to develops systems of control and adjustment to permit the traceability of production throughout the supply chain. SMARTFarming4.0 takes stocks of production time and material used and it sends warning alarms, also remotely, to the operators in the case in which there are some problems [4.4].

As cited above, the IoT solution SMARTFarming4.0 is also applicable to the open field cultivation, with which is possible to collect data in the field and to elaborate with on-board calculations ready-to-use information for the precise agriculture. Additionally, it is possible to develop systems of control and adjustment for an efficient use of farming equipment, to monitor and traces all the activities carried in the field and to control the performance of the equipment used in order to avoid downtime through efficient management [4.4].

The advantages of the use of the SMARTFarming4.0 solution are the same for the both versions and they are [4.5]:

- compatibility with other supply chain and climatic control systems;
- constant georeferencing of all variables;
- wired or wireless connection;
- low energy consumption;
- availability of real time data collection and analysis along all the supply chain;
- interconnection with any type of new or existing plants and machinery.

2.2 The clients

The product developed by *Technophylla srl* is addressed to the builders and suppliers of farming machinery and production system providing a IoT solution in order to monitor remotely the machinery for diagnostic or corrective purposes, to prevent or to resolve equipment downtime and to perfectly know the behaviour of the components with the aim to improve the quality and the reliability of the machinery [4.4].
Depending on the client requirements, the SMARTFarming4.0 can be supplied in three different ways [4.5]:

1. on premises, installed on the single working station of the client;
2. as a software service, which is available on demand either on the portal or mobile device. It can be provided as a pay-for-use logic;
3. with white label, in the case in which the builders and suppliers partners wish to provide a platform under your own brand for the services of their machinery sold all over the world.

The electronic components of the IoT solution provided by *Technophylla* are designed in order to be integrated with the different machines through various protocols, like CAN-BUS, MODBUS, PROFINET, ISOBUS, multiformat file exchange or through digital or analogue Input/Output direct connections with clean contacts of switchboards. In this way, the interconnection and the control of any new or existing machinery or plant is permitted [4.4].

2.3 PhyllaLab

PhyllaLab is the most advanced area in the firm, which aims to obtain horticultural products with higher nutritional value and improved organoleptic properties in greenhouse and vertical farms, than those produced through traditional open field [4.5]. Every year, *Technophylla* invests 30% of its balance sheet in activities regarding R&D. This project is carried out with the collaboration of *Edo Radici Felici*, which is the first Italian company that has consolidated the Airfloating technology for the production of the horticultural products in soil-less cultivation. With this collaboration, in addition to better characteristics of the crops yield, the aim is to demonstrate that the indoor farming allows to reduce of about 95% the use of water and nutrients, to delete the use of pesticides and of soil, to reproduce the optimal light intensity for each phase of plant growth in order to obtain an higher energy efficiency of the system, reducing the energy consumption [4.4].

In this project, the IoT solution SMARTFarming4.0 in soil-less cultivation has to actively monitor and check all the environmental variables, in order to ensure an optimal setting for the plant growth. The main parameters to control are the light intensity, the temperature, the humidity, the nutrient solutions uptake and the ventilation. The value of these variables change depending on the type of the plant and the growth phase of the product, aiming to optimize the production in terms of quality and time [4.5].

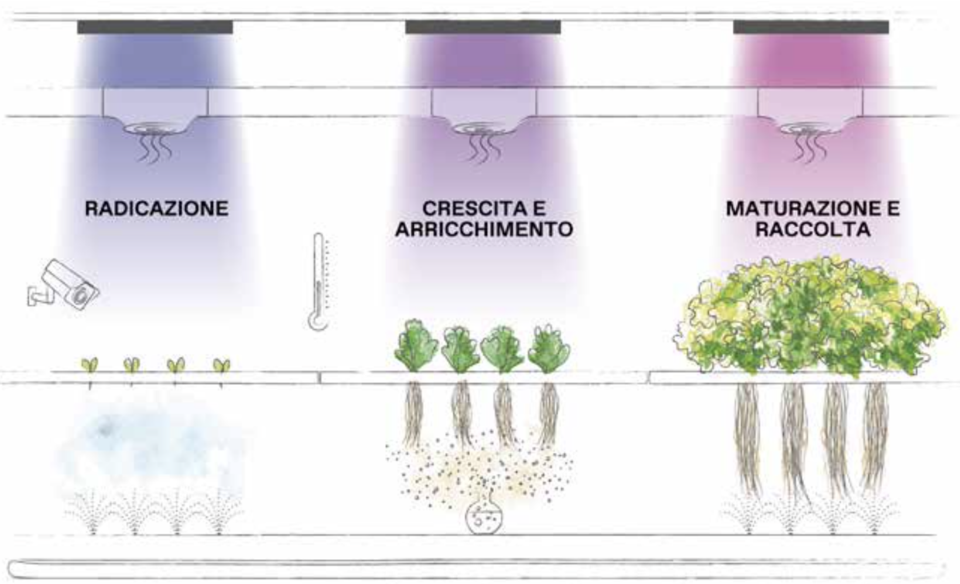

Figure 2.3: *PhyllaLab* Airfloating technology [4.4]

2.4 The goals for 2030

Technophylla srl, through *PhyllaLab*, has set different goals to reach for the 2030, which are [4.5]:

- protect the environment;
- reduce the use of soil and water;
- drastically reduce the use of fertilizers;
- avoid the use of pesticides;
- increase energy efficiency;
- improve the quality and quantity of crops through processes of bio strengthening of the same crops;
- reuse existing disused industrial infrastructure through different techniques of cultivation, such as aeroponic production plants.

The precision agriculture based on IoT technologies and data collected on site help to decrease the environmental impact of the agricultural sector, helping the producers to understand where, when and how they can improve the techniques. In this way, the agricultural practices become more sustainable and, on the other hand, the products have higher quality, the productivity increases and, finally, the ability to adapt to climate change and extreme environmental conditions is strengthened [4.4].

Technophylla supports the digital transformation of the small and medium-sized enterprises (SMEs), operating in the agrifood chain with a solution for both indoor and outdoor cultivations. With *PhyllaLab*, the firm promotes the integration of traditional agriculture with innovative techniques, as soil-less aeroponic technique, which represent new solutions for the future horticultural production, in such a way as to support production models characterized by low impact on land, water, fertilizers and pesticides use, as well as high quality production and low energetic and environmental impact. The result is not only the sustainability aspect, but also a product more healthy and safely from a nutritional point of view. Moreover, this types of indoor cultivation can be realized in urban context, exploiting disused buildings and contributing to supply products at km0, reducing the environmental impact due to transports [4.4].

Thanks to the application of technologies with the aim to develop systems for the planning, the process, the monitoring, the control and the traceability of the entire production cycle, *Technophylla srl* promotes the adoption of solution which help to fight climate change and its consequences, to protect, restore and promote the sustainable use of natural resources [4.4].

Chapter 3

The IoT architecture

The *Internet of Things* (IoT) refers to a network of physical objects, which are provided of sensors, software and other technologies with the aim of connecting and exchanging data with other devices and systems over the Internet. These devices range from ordinary household objects to sophisticated industrial tools.
In the last few years, the application of the IoT has rapidly increased, making this type of technology one of the most important of the 21st century. The number of IoT connected devices in 2021 was increased by 8% and it is expected that this number can reach 27 billion by 2025, increasing of another 22% [4.7].
The expression *Internet of Things* was used for the first time in 1999 by Kevin Ahston, an British engineer, co-founder of the Auto-ID Center of Massachusetts, in close connection with RFId (Radio Frequency Identification) devices [4.8].

There are numerous sectors, which can benefit using the IoT in their business process. Some of them are:

- Manufacturing: using a production-line monitoring can give a competitive advantage because it is possible to enable proactive maintenance on equipment when the sensors detect a possible failure [4.6];
- Automotive: beyond the benefits in the production lines, the IoT can be applied in the vehicles on the road, alerting the driver with alarms and recommendations [4.6];
- Retail: it is helpful an IoT system to monitor the inventory, to improve the customer experience, to optimize the supply chain and to reduce the operational costs [4.6];
- Healthcare: through the implementation of the IoT, it is possible to monitor and to provide treatments to the patients according to the fluctuations of the health conditions [4.6];

- Finance: connected devices can help the users to take good financial behaviour, without any spending indulgent behaviour [4.9];
- Hospitality: the IoT industry has helped to provide a personalized experience to guests reducing their waiting time [4.9];
- Transportation and logistics: the two core aspects of this sector are the timing and the speed of the activities. With the use of IoT, the companies can be smarter and more efficient thanks to the automation and business process optimization [4.9];
- Agriculture: the sensors can be applied in this field in order to monitor the condition in which the plants grow, assuring the best environment depending on the species to cultivate [4.6];
- Smart home: nowadays, this application of the IoT is becoming more and more implemented. This consists in connecting smart devices, such as thermostats, air conditioners, TVs and so on, in order to monitor them remotely using a tablet or a smartphone. This allows these devices to perform scheduled and automated tasks [5.0].

3.1 How IoT works

The goal of the *Internet of Things* is to connect multiple devices at the time to the Internet in order to facilitate the interactions that can occur between man-to-machine and machine-to-machine.
The IoT is composed by four different components [5.1]:

1. Sensors/devices: these elements are essential in order to collect the data necessary for the analysis of the system from the environment. The collected data can have different degrees of complexity, depending on the application, ranging from a temperature monitoring sensor to a complex full video feed. The sensors can pick data with a specific timing preset from the owner of the system. A device can have multiple sensors, which can be bundle together to do more things than just sense things;
2. Connectivity: the sensors, which are connected to the cloud, send the collected data to the cloud infrastructure through a medium for the transportation, such as Wide-Area Network (WAN), Bluetooth, Wi-Fi, cellular networks and many others. Depending on the IoT system, it is possible to choose a specific medium, basing the choice on the different specification of them, as power consumption, range and bandwidth;

3. Data processing: a dedicated software processes the data, which are collected and send from devices. This step can be very fast and easy, as checking that a value, like the temperature, is in a preset range, or it can be more complex, such as identifying objects using computer visions or video;

4. User interface: lastly, the collected information are made available to the end-user, through different ways, like triggering alarms on the mobile phone or notifying texts or emails. Sometimes, the users can have access to an interface through which they can actively check in on their IoT system. The choice of the user interface depends on the IoT application and the complexity of the system. Using the interface, the user can remotely make changes in order to adjust parameters. Otherwise, the system can perform some actions automatically, after developing and establishing the rules to be followed.

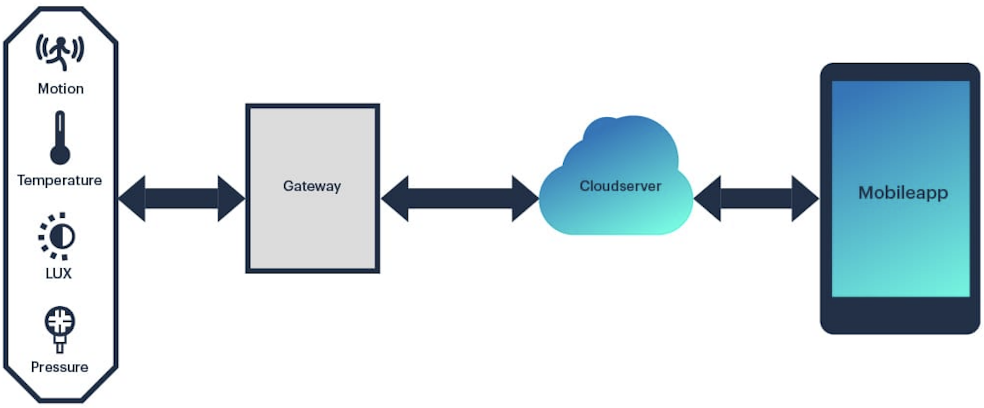

Figure 3.1: The components of the IoT system [5.2]

3.2 ISA-95

ISA-95 is an international standard for the integration of enterprise and control system, which consists of models and terminology, developed by the International Society of Automation. The official name of this standard is *ANSI/ISA-95 Enterprise-Control System Integration*. This standard is the successor of the *ISA-88* because it is not applicable to newest technologies, as IoT and smart machinery.
The standard allows the development of an interface for communication between various level of manufacturing enterprise based on the Purdue Reference Model, which is a reference model for enterprise architecture, developed by Theodore J.

Williams [5.3].

ISA-95 specification standardize information models and terminology, making information exchange between enterprise systems, control functions and manufacturing operations systems frictionless. This standard can be applied to all types of industries and processes in order to facilitate the communication between all the actors of the supply chains [5.3].

The ISA framework is characterized by five different levels (0-4), as shown in figure 3.2. The first three levels are composed by activities directly involved in manufacturing and information about materials, personnel and equipment. These activities can be critical for at least one of the following reasons: plant safety, plant efficiency, plant reliability, product quality and regulatory compliance. The fourth level includes activities related to manufacturing operations, as the optimization of the processes. Lastly, the decisions about logistics and business planning, like production levels and material types, are taken in the fifth level [5.3].

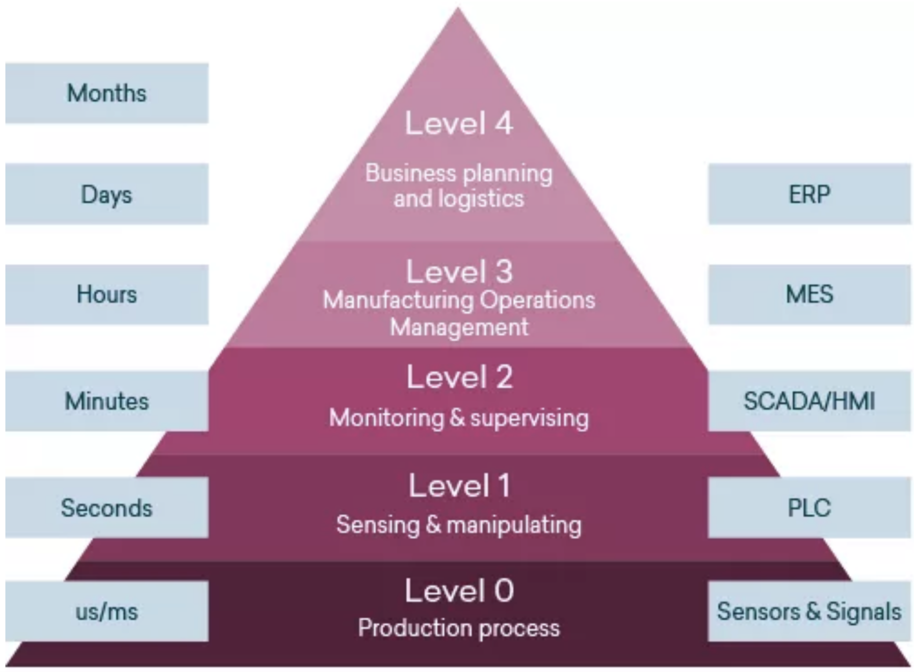

Figure 3.2: The levels of ISA-95 [5.4]

More in details, the levels and their roles are the followings [5.4]:

- Level 0: Production process. This is the lowest level and it corresponds to the actual physical environment, from which the data needed are collected. These ones are often at very small granularity, but in large volume because they are measured very frequently, usually every some milliseconds or even down to μ seconds;

- Level 1: Sensing and manipulation. This level includes sensors and valves, which has the role to collect the data from the environment and to send them to a controller or a subsystem. The sensors are used for all the parameters for which the assets of the manufacturing environment have to be 'sensed', as temperature, pressure and cycle-count. On the other hand, the valves are used for the assets, which have to be 'manipulated', as the shutting off a valve or turning equipment on or off. The data are usually collected in seconds;

- Level 2: Monitoring and supervision. The system and the controllers, at this stage, has to supervise and regulate the manufacturing environment. Automation control hardware, combined with some software, as SCADA and HMI, are used to manipulate and control the plant systems and assets. This may include shutting down a pump or simply watching the collected values. Actions are measured in minute;

- Level 3: Manufacturing Operations Management. The activities performed in this stage link the digital and the physical world. The actions typically performed in this level are scheduling, workload balancing and optimization of the processes, aiming to reach the production goals. The level involves different software solutions, as Computerized Maintenance Management Systems (CMMS), Supervisory Control and Data Acquisition (SCADA) and Advanced Process Control (APC), to manage the different activities performed in the plant, as quality, integrity and production of each system's information and span of control, emissions and maintenance. Typically, it is measured in minute;

- Level 4: Business Planning and Logistics. In this level, it is necessary to align the business goals and the manufacturing operations. The data created in the previous levels are necessary in order to perform a correct analysis, using some software, as Enterprise Resource Management (ERP), Supply Chain Management (SCM) and CMMS. The time frame for this stage is typically of some weeks, or even months.

The values for all the levels of the ISA-95 framework are provided by the IoT, predominantly for the first three layers.

3.3 The system

An IoT architecture has been developed for an aeroponic growth system in order to manage the collection of the data from the field and to create database for the collection and the analysis of these data. The approach used for the the analysis is based on the ISA-95 framework, particularly on the bottom level, so in the first four levels.

3.3.1 IoT model of the system

The IoT model of the system developed for the aeroponic system is described in the figure 3.3.
The model is characterized by four different levels, a modified version of the framework ISA-95. In particular [5.5]:

- Level 0: Field Layer. In this first level there are the sensors and devices for the perception and control of the environment of the system analysed. They includes the control of the lamps, pumps and valves in order to provide the right quantity of each parameter for the growth of the plant. There are different types of sensors, which collect data from the system, as the humidity and temperature ones, or pH and electrical conductivity (EC). In this layer, all the physical phenomena are converted in digital, or viceversa. In this level there is the interaction between the system and the physical world.

- Level 1: Edge and Controller Layer. In this stage the data are collected by the Raspberry Pi, which is a single-board microcomputer. Moreover, there the Raspberry Pi communicate with a Graphical User Interface (GUI), which is a local interface near the system, used for monitoring and control. If there are more systems, for each of them there is its layer. Both components of this level use *Node-RED*, which is a programming tool for wiring together hardware devices.

- Level 2: Platform Layer or Cloud Computing Layer. The collected data by the Raspberry Pi in the previous layer are, then, send to a MQTT (Message Queuing Telemetry Transport) broker, which is a TCP/IP data transmission protocol based on a publication and subscription model that operates through a dedicated message broker. In the system, it is used the software *Mosquitto*, which is an open source message broker that implements the MQTT protocol. Subsequently, the data are sent to databases, which are uses for conducting some specific analysis. The databases, usually, are not in the physical area, but offload. If in the analysis there are more systems, for each of them there is a database and all of them are stored together in the Cloud. Moreover, the MQTT Broker can be used to manage the devices and user access. The software used for the database in the system is *PostgreSQL*, an open-source object-relational database system. In the database of the system there are three attributes: topic, value and timestamp. The topic describes what type of information is collected: CO_2, pH, Electrical Conductivity, temperature and light intensity. The timestamp express when the value is collected. The use of open-source software allows to create specific IoT architecture for the system. This layer is the core of all system.

- Level 3: Application Layer/User Interface Layer. This is the level where the interface with the user takes place through a Graphical User Interface, which uses the *Node-RED* software. This layer is the interaction between the system and the human being. Through the GUI it is possible to get charts and trends, taking data from databases, about every type of parameter, which is collected in the system. This kind of data analysis can be used as support for decision making.

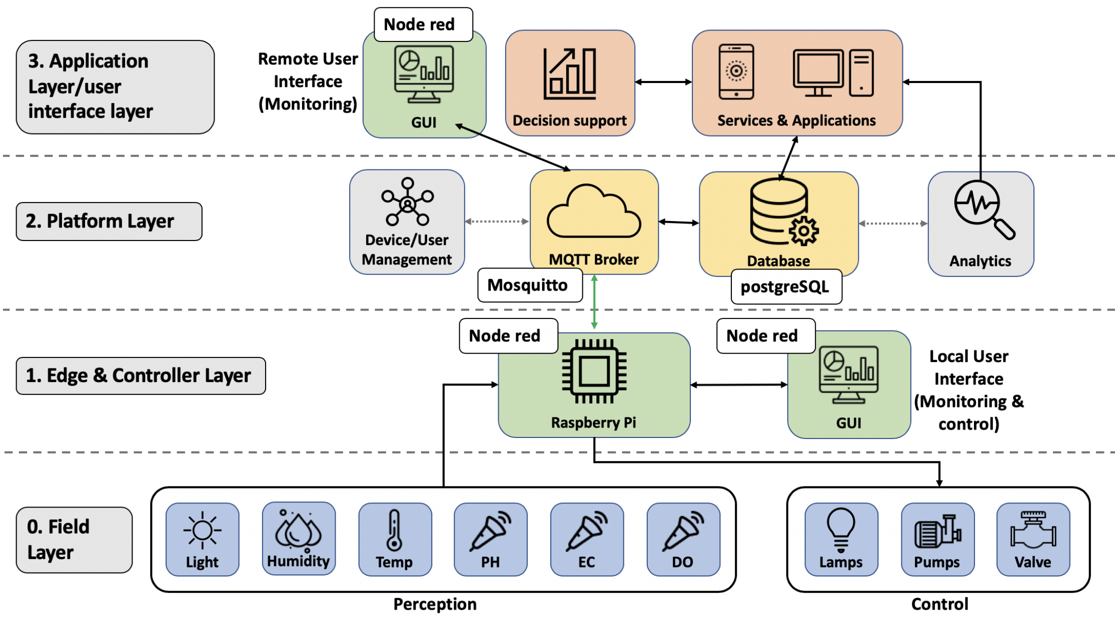

Figure 3.3: The IoT model of the system [5.5]

3.3.2 The IoT architecture of the system

In the analysed system, the focus is on the first two bottom layer of the ISA-95 framework, the Field Layer and the Edge and Controller Layer, as shown in figure 3.4. It is a more detailed description of how the sensors and actuators are connected to the Raspberry Pi, which is the center of the diagram.

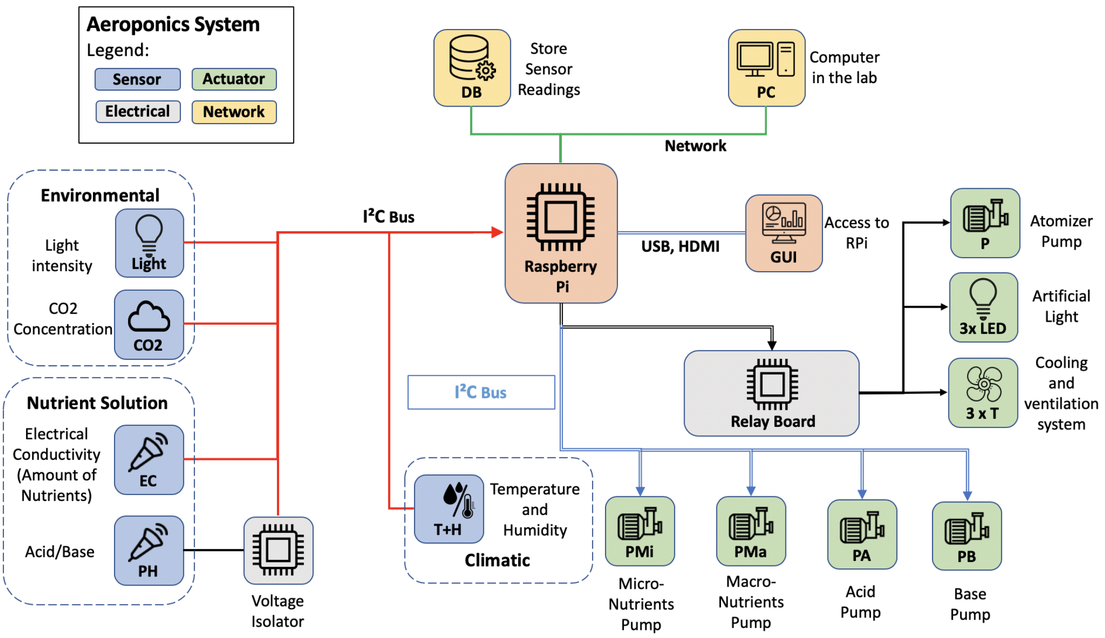

Figure 3.4: The IoT model of the system

Sensors

The sensors are divided in three macro area:

- Nutrient solution area, in which there are electrical conductivity and pH sensors. They are inserted in solution reservoir.
- Environment area, which is characterized by the sensors to monitor the conditions of the chamber with the aeroponic system. Particularly, the system is composed by light intensity and CO_2 concentration sensors.
- Climatic area, which includes temperature and humidity sensors. They are installed in the growth chamber.

All the sensors communicate the collected data from the system to the Raspberry Pi through I^2C, which is a powerful and popular bus used to communicate between

a master (or multiple masters) with one or more slave devices. This type of bus is a standard bidirectional interface, allowing the communication between the master and the slave devices. These lasts cannot send data unless they have been addressed by the master. Each slave device in the I^2C bus has a unique address in order to be differentiated from the others. Usually, the slave devices require to be configured in order to set the communication behaviour to be taken, this is done by writing on the registers, which is a part of the slave's memory. A device can have more than one register, where the data are stored, read and written. The master must write information into these registers in order to instruct the slave device to perform a task, such as sending or receiving data.
In the system analyzed, the data have only one direction: they are sent from the sensors, which are the slave devices, to the Raspberry Pi, which is the master. When the master wants to receive and read the data, it has to send a START condition to the slave devices and it addresses the slave-transmitter. Subsequently, the master-receiver sends the request to read a specific register to the slave device and the master starts to receive the wanted data, until it terminates the transfer with a STOP condition [5.6].

The detailed technical information of the sensors, which are installed in the growth chamber of the system, are the followings:

- pH sensor: it provides information about the acidic or basic nature of the nutrient solution. The value of the pH must be kept between 5.5 and 6.5 in order not to compromise the growth of the plant. In the system, this parameter is controlled by the pH kit, produced by *Atlas Scientific*. The kit is composed by the sensor, know as *Lab Grade pH Probe*, which is characterized by an internal double junction single/single chloride, allowing to read the pH of protein-rich solution without damaging the probe. The body of the sensor is made of extruded epoxy, giving to it the resistance necessary for strong basis and acid. Additionally, there is a transmitter, the *EZO pH circuit*, which, with a simple command, is able to read accurately pH. The transmitter uses an operating voltage between 3.3V and 5V, the data format is the ASCII and protocol used is the I^2C, of which as default address is 99. Moreover, the transmitter is compliant with the standard ISO 10523 (International Standard Organization). Both the components of the kit have a range from 0 to 14, an accuracy of ± 0.002 and a resolution of 0.001. Additionally, in the kit provided by *Atlas Scientific* there are six calibration solution pouches, one pH storage solution pouch and an electrically isolated *EZO Carrier Board*, with which it is possible to connect one circuit to a separate CPU (Central Processing Unit), without the need of a bread board and external isolator. It uses a voltage input of 3.0V-5.0V [5.7]. Because of the very high sensitivity of this sensor, it is necessary to isolate it with the help of a voltage isolator. For this purpose, the *Basic EZO Inline Voltage Isolator*, provided by *Atlas Scientific*, is used. It has a voltage output of 3.9 ±0.07 and a voltage input between 3.0-5.0V [5.8]. Both the Carrier Board and the Voltage Isolator use the I^{2}C protocol.

Figure 3.5: pH Kit *Atlas Scientific* [5.7]

- Electrical Conductivity (EC) sensor: it measures the total concentration of salts in the nutrient solution, pointing the total ionic concentration and the strength of the nutrient solution. The optimal range to be kept is between 1.5 and 2.5 dS m^{-1}. It is used the Conductivity K 1.0 Kit, provided by *Atlas Scientific*, which is composed by a *EZO Conductivity Circuit*, a *Conductivity Probe*, a *Electrically Isolated EZO Carrier Board* and two calibration solutions. The conductivity circuit, which is the transmitter, uses the I^{2}C protocol, which has the default address 100. The operating voltage is between 3.3V and 5V, the data format is ASCII, the EC reading time is of 600ms and the range is 0.07 and 500,000 μS/cm. Moreover, it is compliant with the standard ISO 7888, which is about the determination of the electrical conductivity. The sensor, which is the conductivity probe, has been designed to provide stable and precise readings free of fringe effect over a broad conductivity range. It has a range between 5 and 500,000 μS/cm, a response time of 90% in 1s and a temperature range between 1-100°C. Both the circuit and the probe have an accuracy of ± 2%. The carried board is the same which is used for the pH sensors [5.9].

Figure 3.6: EC Kit *Atlas Scientific* [5.9]

- CO_2 sensor: it is used to check the air quality in the aeroponic chamber. The CO_2 concentration influences the plant growth, affecting the respiration of the roots and the nutrient absorption. The *EZO-CO2 Embedded Carbon Dioxide Sensor*, provided by *Atlas Scientific*, is the sensor used in the chamber, which is a compact Non-Dispersive Infrared (NDIR) that gets right in the point, providing the CO_2 in ppm. The range that the sensor can read is between 0 and 10,000 ppm and can be used only at the atmospheric pressure. It has a response time of one reading per second and a resolution of 1 ppm. The accuracy is about ($\pm$ 5%) + ($\pm$ 50ppm). The protocol which is used to transmit the data is the I^2C [6.0].

Figure 3.7: CO_2 sensor *Atlas Scientific* [6.0]

- Light Intensity sensor: the sensor used is the *MQ-500: Full-Spectrum Quantum Meter*, provided by *Apogee instrument*, and it measures the Photosynthetically Active Radiation (PAR) inside the growth chamber. Differently from the other product in the market, this quantum light sensor presents a laboratory-grade PPFD (Photosynthetic Photon Flux Density), or 'quantum', optical detector in order to accurately measure the light intensity in μmol m^{-2} s^{-1} of the specific wavelengths emitted by LEDs, sunlight and all the other light sources utilized for the plant growth. Quantum sensor uses a precision silicon photodiode detector, a custom optical filter, and an acrylic diffuser all housed in a self-cleaning, dome-shaped, anodized aluminum sensor head. The sensor head is potted solid with epoxy for years of use in harsh environments, including underwater. The range of measurement of the sensor is between 400 and 700nm, with an accuracy of 5%. The sample mode will collect the data about the light intensity every 30 seconds, and after 30 minutes, it makes the average of the last 60 measurements. It can record up to 99 measurement, once this is reached, the sensor overwrites the oldest values [6.1].

Figure 3.8: Light intensity sensor *Apogee instrument* [6.1]

- Temperature and Humidity sensor: it was studied that the temperature and the humidity are two of the most important factors, which influence the growth of the plants in the chamber, particularly the roots' growth, the transpiration and respiration, the flowering and the dormant period. Both the temperature and the humidity must be kept in a range, which is specific for each species of plant. For this reason, the use of the sensor helps to check that the two parameters are in the range or if it is necessary to intervene in order to bring them back inside the preset range. The sensor used is *SHT-30 Temperature/Humidity Sensor*, by *Adafruit*. The sensor includes a dual-use sensor module from *Sensirion*, a company with great experience in the development and production of sensors, in a sintered metal mesh encasing. The casing is weatherproof and will keep water from seeping into the body of the sensor and damaging it, but allows air to pass through so that it can measure the humidity outside. The relative humidity of this sensor is of ±2% and the accuracy for the most of the use is ±0.5°C. It uses the I^2C protocol, with communication speed up to 1MHz. The supply voltage range is from 2.4 to 5.5V, the temperature range is -40-125°C [6.2].

Figure 3.9: Temperature and Humidity sensor *Apogee instrument* [6.2]

Actuators

The actuators present in the system can be divided in two macro categories: the ones directly linked with the Raspberry Pi and the ones which needs a Relay Board in order to communicate with the Raspberry Pi.

In the first category, there are four different types of peristaltic pumps, which are used to manage the concentration of the pH and of the nutrients in the solution. The pumps for the pH, particularly, are used to add acid or base to the nutrient solutions, depending on the value of the pH monitored by the sensor. On the other hand, the nutrients pumps have to provide the micro-nutrients or macro-nutrients,

depending on the concentration of the solution, controlled by the Electrical Conductivity sensor.
In the peristaltic pump, the head of the treated fluid is impressed by a bottleneck that runs along the pipe. The pump is composed by one rotor, to which two or more rollers are applied, throttle the pipe and the fluid can move. These types of pump can be used for every categories of fluid [6.3]. In the system, the four pumps are all equal and they are the *EZO-PMP Embedded Dosing Pump*, provided by *Atlas Scientific*. They are characterized by the flow rate between the 0.5ml/min and the 105ml/min, the accuracy of ± 0.01 and they use the I^2C protocol. Their operating voltage range is different between the logic and the motor. For the first one, it is between 3.3 and 5V, instead, for the second it is 12V – 24V. The data are provided in ASCII [6.4].

Figure 3.10: Peristaltic pumps *Atlas Scientific* [6.4]

The other actuators are linked to the Raspberry Pi through a Relay Board, which is a board able to control equipment with high voltage, isolating the Raspberry Pi. In the system, there is the *8 Channel 5V Relay Shield Module*, by *SunFounder*, which is composed by 8 channels and each one needs 15-20mA Driver Current. It can be controlled directly by a Microcontroller [6.5]. Moreover, it is used in the chamber for ON-OFF control on the actuators, which do not use the I^2C protocol.

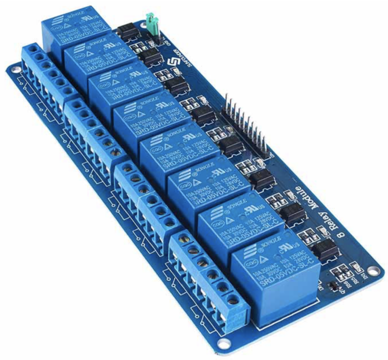

Figure 3.11: Relay Board *SunFounder* [6.5]

Linked to the Relay Board there are the following equipments:

- Atomizer Pump: it is used for the irrigation of the aeroponic growth chamber. The selected pump has a dimension of 60x40x32cm and a mesh filter. It is composed by an internal circuit equipped with nozzles, which are used to spray the nutrient solutions in the aeroponic system. There is also a solution discharge tap. The atomizer pump was provided with the chamber by the supplier and it is the model *BF-4800*, produced by *Bao Feng*. The characteristics of the component are: the voltage is DC 12V, with a maximum of 6.5A, the flow rate is 5L/min, the exercise pressure is 0.03MPa and the maximum rated pressure is 0.7MPa. The power of the pump is 80W [6.6].

Figure 3.12: Atomizer Pump *Bao Feng* [6.6]

- LEDs: for the growth of the plants, the light plays a key role. It is important to provide the right intensity of light, because a lack of it can compromise the photosynthesis process, impacting the characteristics and the develop of the plants. For the system, three LED lamps, provided by *Elmo s.r.l*, has been installed, each of them have a voltage of 24V and a length of 70cm. They has been selected because the high blue-intensity, of which they are composed, is suitable for growing leafy vegetables. Moreover, the average lifetime of the LEDs is 5-6 years, with 24 hours of use, making the maintenance cost reduced compared to the traditional lighting [6.7].

- Three fans: they are used for the cooling and ventilation system. The selected fans for the system are provided by *Rapid Air Movement*, and they present two different speeds: 50 or 60Hz. The impeller size is 180mm, the power 20W and the voltage between the 220 and the 240V [6.8].

Figure 3.13: Fan *Rapid Air Movement* [6.8]

Microprocessors

The "brain" of the system is the Raspberry Pi, a single-board microcomputer, in particular, the model used is the *Raspberry Pi 4 Model B*, which has a 40-pin GPIO (General Purpose Input/Output) header, to connect sensors, actuators,the relay board and the other peripheral. Its interface has two 5v outputs and the remaining pins are general purpose 3.3V pin, meaning outputs are set to 3.3V and inputs are 3.3V-tolerant.
The Raspberry Pi runs a *Broadcom BCM2711*, a four core and four threads processor with a maximum frequency of 1.5GHz and 1MB of cache. It has a maximum memory capacity of 8GB, the maximum memory bandwidth is 4.4GB/s [7.0], and it has 4GB of RAM (Random Access Memory) [6.9]. . It is also provided with a few peripherals to connect the board to the network such as Wi-Fi, Bluetooth and Gigabit Ethernet port to communicate with a remote database.
The Raspberry Pi uses the I^2C protocol to communicate with the sensors and trigger them to send the data collected in the environment, with a specific time lapse. After that, the data are sent to the Local User Interface and the MQTT Broker, which sends, in turn, the data to the database.

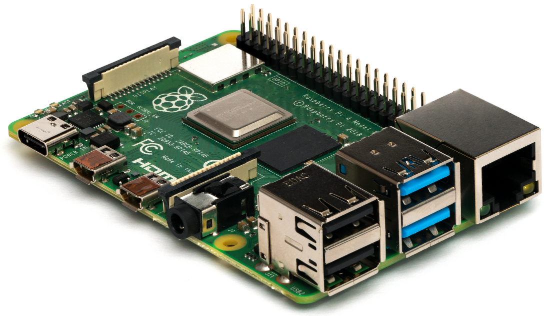

Figure 3.14: Raspberry Pi 4 [6.9]

Software

As described at the beginning of the section 3.3.1, there are different software, which are used in the system. All the software are free and open-source, allowing to personalize the code adapting it to the specific system. The software used are the followings:

- Node-RED: it is a programming tool for wiring together different hardware devices. It provides a browser-based flow editor, which helps to wire the numerous flows using the wide range of nodes in the palette. Particularly, it links the data collected from the sensors to the Cloud, connecting hardware and software. It is possible to create JavaScript function, using a rich text editor. The programming tool is built on Node.js, making it ideal to run at the edge of the network on low-cost hardware such as the Raspberry Pi as well as in the cloud. All the flows created are, then stored using JSON, which can be easily shared with others. Moreover, it has a wide libraries availability and it is a graphical programming tool, allowing the user to focus on the logic of the development rather than on the syntax and debugging [7.1]. The system uses the Raspberry Pi for the Local User Interface and the Remote User Interface.

- Mosquitto: this software is an open-source message broker, which implement the MQTT protocol. It can be used for all types of devices, from the low power single board computers to full servers. The MQTT protocol provides a lightweight method of carrying out messaging, used for machine-to-machine communication. It makes the protocol suitable for the Internet of Things messaging. Additionally, the Mosquitto project provides a C library for the MQTT clients [7.2]. It is used for the MQTT Broker.

- PostgreSQL: it is an open-source object-relational database system, characterized by many feature, which help developers to build applications, administrators to protect data integrity and to manage data no matter how big or small the dataset. Moreover, it is highly extensible and it supports many of the features required by the SQL standard. Some of the features which can be found in PostgreSQL are: data integrity, data types, concurrency, performance, reliability and so on [7.3]. This software is used for the database, reachable through the local network.

The growth chamber

The chamber selected for the aeroponic system is the *Mammoth Classic150*, which is 150x150x200cm grow tent, of which the internal coatings, made of 600D Mylar, guarantee maximum light reflection, instead, the external layer prevents the passage of the light. Inside the tent, there are supports for lighting system, aspirators and odor treatments filter. The air exchange is guaranteed by the holes for the aspirators as well as by the meshed side openings for passive ventilation. The structure is made by 19mm steel tubes, assuring structural stability and rigidity [7.4].
Inside the chamber, there is the plant bed, which consist of jute dowels suspended on a plastic mesh. The dimensions are 60x40cm, allowing the cultivation of 228 plant at the same time.

Figure 3.15: The growth chamber and the aeroponic system

In the figure 3.16, a technical scheme of the growth chamber is reported. As shown, the CO_2 and the temperature/humidity sensors are located at the top of the structure, above the aeroponic system. The pH and the EC sensors are immersed in the water, under the plant bed. The five pumps, which are connected through cables to the Raspberry Pi, are installed on the side of the system. Moreover, a tube comes out from the atomizer pump, with which the aeroponic system is irrigated. Inside the chamber, there is a system of air conditioning and a fan.

Above the aeroponic system, there are the three LEDs.
The next figures represents the chamber with all the components described.

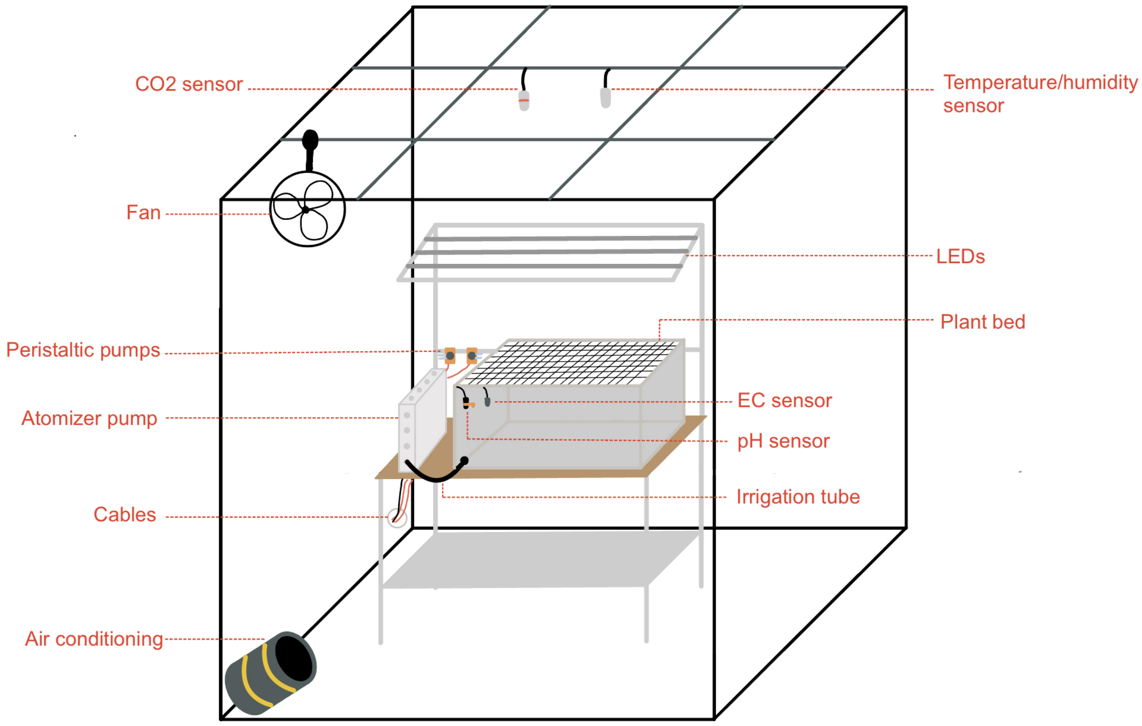

Figure 3.16: Technical scheme of the growth chamber

Figure 3.17: The growth chamber and all the components

Chapter 4

The Entity Relationship (ER) Diagram

The Entity-Relationship Diagram or ER Diagram is a type of flowchart, in which there are shown the relationship between different entities, such as people, objects and concepts within a system. Through the definition of the entities, their attributes and the relationships between them, it is possible to show the logical structure of databases, in order to design or debug them for many different sectors, like software engineering, business information systems, education and research. Usually, the ER Diagram is used together with the Data Structure Diagrams (DSDs), which show how the flow of information for processes or systems are connected, helping the construction of the relational database [7.5].

The ER Diagram has been developed in the 1970s by Peter Chen, a computer scientist, and in the 1976 published the "The Entity-Relationship Model: Toward a Unified View of Data", in which he showed his proposal for the diagram. This model permits to visualize a database that unified other existing models into a single one removing ambiguities, providing a unique framework for database modelling. Before the development of the ER Diagram, there were three different data models for databases: the network model, the relational model, and the entity set model. Each of them has its own strengths and weaknesses, but all of them does not provide a complete view of the database [7.6].

The Entity Relationship Diagram uses different set of symbols, such as rectangles, diamonds, ovals and connecting lines to depict the interconnectedness of entities, relationships and their attributes [7.6].

- Entity: it is something, which is definable, as person, object, concept or event, that can have data stored about it. The entities are expressed as nouns. The shape used to show the entities is the rectangle [7.5].

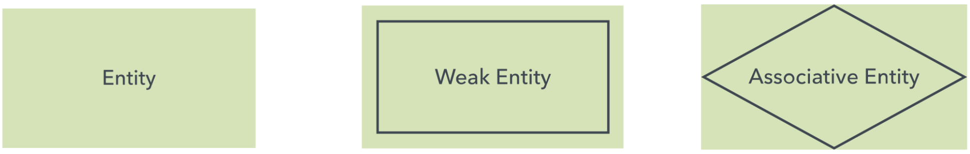

Figure 4.1: The entities in ER Diagram [7.5]

Moreover, there are different characteristics, which can be associated to each entity [7.5].

- Entity type: a group of definable things, such as students and athletes, whereas the entity would be the specific student or athlete;
- Entity set: in this case, the entity is defined in a specific point in time, such as a student enrolled in a class on the first day;
- Entity categories: the entities are, then, characterized as strong, weak or associative. A weak entity needs other attributes to be defined, while a strong one can be defined solely with its own attributes. An associative entity associates two or more entities in the same entity set;
- Entity keys: it refers to the attribute, which defines an entity in an entity set. They can be super, candidate, primary or foreign. The first one is a set of attributes, which together defines an entity in an entity set. The candidate key is defined as the minimal super key, which means that it has the least possible number of attributes to be a super key. An entity set can have more than one of candidate key. A primary key is a candidate key chosen by the database designer to define uniquely an entity set. The foreign key identifies the relationship between entities.

• Relationship: it defines how the entities are linked together. The relationships are thought as verbs. An example of the relationship is a named student, which needs to register for a course. The entities are the course and the student, and the relationship depicted is the act of enrolling, connecting the two entities in that way. The relationships are, usually, shown as diamonds. There can be some entities, which participate more than once in the relationship. This situation is known as recursive relationship [7.5].

Figure 4.2: The relationships in ER Diagram [7.5]

- Attributes: they are properties or characteristics of an entity. They are represented by an oval or a circle. The descriptive attribute is a property or a characteristic of the relationship versus of an entity. For each entities, there could be one or more Key Attributes or identifiers, which are the attributes that permits the relationships between the entities. There are different categories of the attributes [7.5]:
  - Simple: the attribute cannot be further divided and it is atomic, such as a phone number;
  - Composite: they are secondary or sub-attributes, which derive from an attribute;
  - Derived: the attribute is calculated or derived from another attribute, like the age starting from the birthday;
  - Multi-value: it is the case in which there are more than one value associated at the same attribute, such as more telephone number for the same person;
  - Single-value: when there is an unique attribute value.

  The different types of attributes can be combined together, obtaining, for example, simple single-value attributes or composite multi-value attributes.

Figure 4.3: The attributes in ER Diagram [7.5]

- Cardinality: it defines the numerical attributes of the relationship between the entities. It can be [7.5]:

- One-to-one: when there is a correlation between the two entities equal to one. For example, one student is associated to one email address;
- One-to-many: it could, also, be as many-to-one. It is the case in which one entity is linked with many different entities, as one student, which is registered for different courses. On the other hand, each course has a single line back to that one student;
- Many-to-many: it happens when there is multiple correlation with both the entities of the relationship. For example, a student group is associated with multiple faculty members, and viceversa faculty members are associated to multiple students.

For the cardinality, there are different notations, which can be used, as shown in figures 4.4 and 4.5.

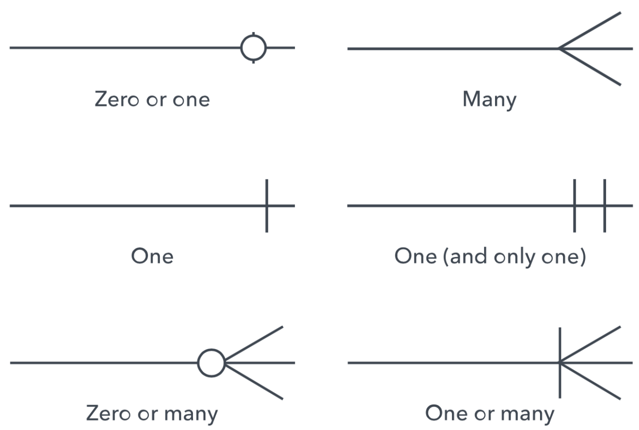

Figure 4.4: The cardinality in ER Diagram [7.5]

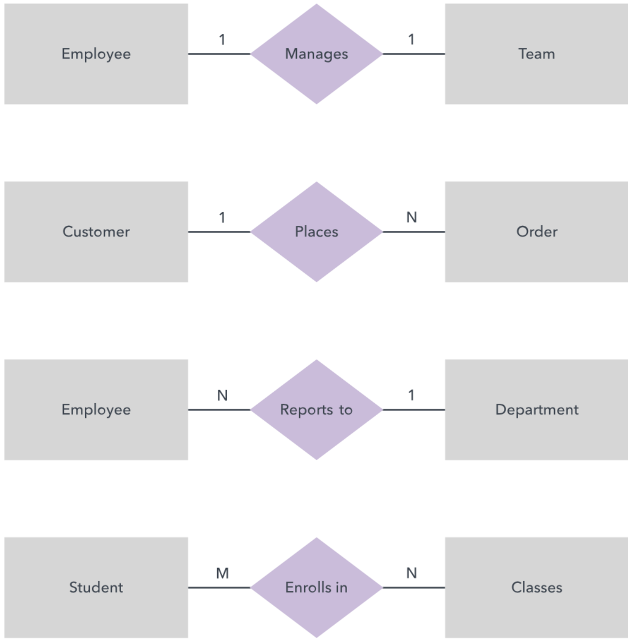

Figure 4.5: The cardinality in ER Diagram - Chen Notation [7.5]

4.1 The ER Diagram for the experiment

During the analysis conducted, the database initially created for collecting the data from the chamber is characterized by three different attributes: the topic, the value and the timestamp. At each specified time interval, the sensors, through the Raspberry Pi, send the data collected from the field to the database, associating the value to the parameter monitored, as described in the chapter 3, section 3.3.1.

In this section, the objective is to create an ER Diagram, that can be used with one or more chambers, in order to register both the condition of the environment, in which the plants grow, and the specific measurement taken on the plant itself.

As shown in figure 4.6, each entity is characterized by its attributes, of which at least one is the Key Attribute.
In the following list, each entities, with its attributes and relationships with the others ones, are described:

- Chamber: the entity chamber presents a unique attribute, which is also the Key Attribute: ID Chamber, that identifies the chamber considered. It is linked with the systems, which are present in the chamber. The cardinality of this relationship is one-to-many or (1, N) since there may be multiple systems in the chamber.

- System: it is identified by the Key Attribute ID System, which defines the system that is under analysis. It is linked with sensors and plants with a cardinality of one-to-many because in both situations, in the same system there can be one or more plants or sensors. Moreover, this entity is linked with the chamber one with a cardinality of one-to-one because each system is in a specific chamber.

- Plants: this entity is characterized by two Key Attributes: the ID of the plant and the the cycle number. Moreover, there are two additional attributes for the sewing and the harvesting date. The position of the plant in the plant bed is another attribute: it is important to register that because the location can be cause of variations in the KPIs measurements. The plants entity is linked with the system, with a cardinality of one-to-one or (1, 1), because a plant can only be present in one chamber, and with the measurements with a cardinality of one-to-many, due to the multiple measurements, which can be collected for each plant.

- Measurements: this is a weak entity because it can exist only if there are plants and KPIs to be measured. For this reason, the Key Attributes are all the identifiers of the plants and KPIs entities and the date at which the measurements are collected. Additionally, there is another attribute that is the value measured. This entity is linked with the plants and KPI entity with a cardinality of (1, 1) because at each plant corresponds one measurement for each type of KPI.

- KPI: the Key Attribute for this entity is the ID of the parameters, which identifies the KPI analysed. There is an additional attribute, that is the name of the KPI. In particular, the parameters collected for each plants are:
  - Fresh Weight;
  - Dry Weight;
  - Leaf Area Index (LAI);
  - Number of leaves;
  - Stem Length;
  - Stem Diameter;
  - Bacterial Load;
  - NO_3;
  - Minerals.

This entity is linked only with the measurements with a cardinality of one-to-many, because for each KPI there may be more measurements.

- Sensors: this entity identifies the sensors in the system, which have the role to monitor the conditions of the environment. There are two different attributes: the ID of the sensors, which is also the Key Attribute, and the name of them. The sensors are the followings:
  - Temperature;
  - Humidity;
  - CO_2;
  - pH;
  - EC;
  - Light Intensity;

  This entity is linked with the system with a cardinality of one-to-many, because there can be more than one sensors of each type in the system considered, and with the entity readings with a cardinality of one-to-many, because for each sensors there are multiple data collected.

- Readings: as for the case of the entity measurements, this is a weak entity, therefore it can only exists if there are sensors in the system. Consequently, the Key Attributes are the ID of the sensor and the time at which the value, that is an attribute, is collected. The readings entity is linked only with the sensors with a cardinality of one-to-one, because each value collected from the environment is defined for a specific sensor.

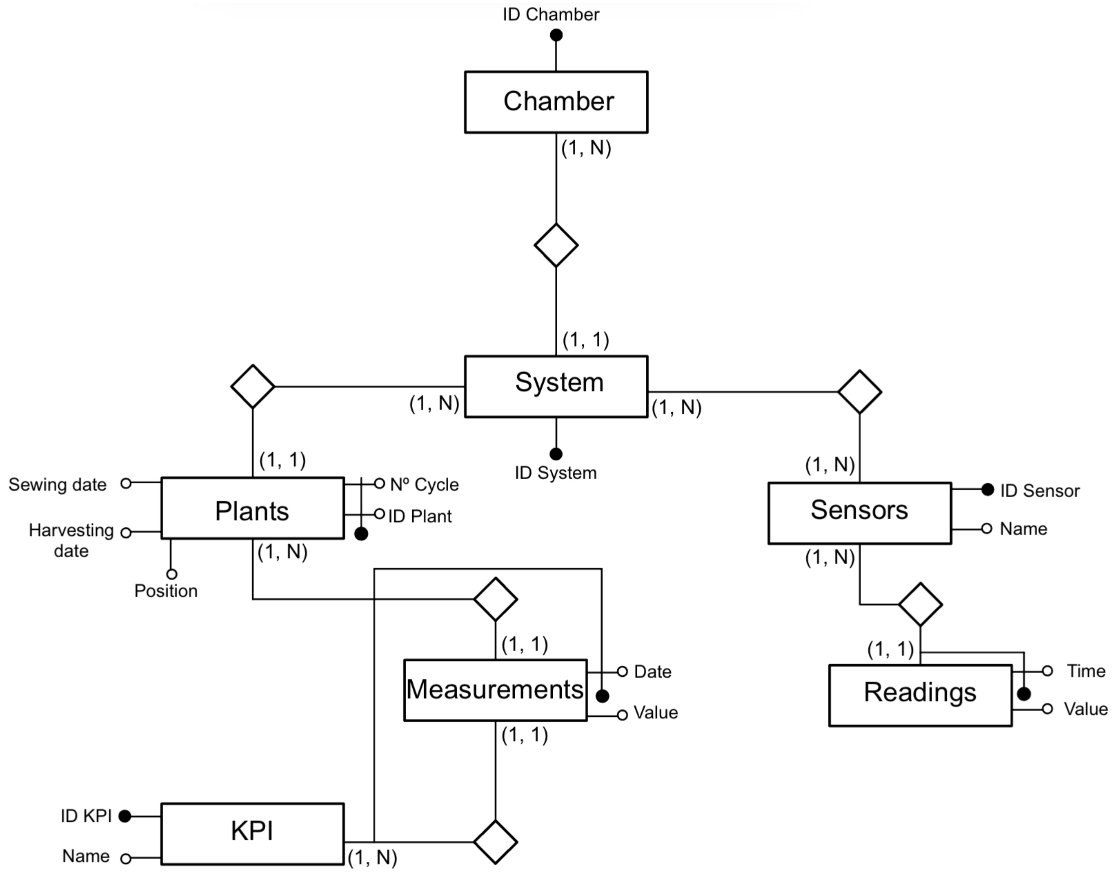

Figure 4.6: ER Diagram

Chapter 5

The experiment

The experiment, performed at the Polytechnic of Turin, consists in analysing some characteristics of the lettuce in different time span. In particular, the aim of the experiment is to follow the growth of the lettuce, collecting the results after one, two and three weeks from the sowing. In this chapter, particular focus is given to the two studies which have been conducted: the first on the light intensity with the aim to uniform it, and the second one is on the layout of the lettuce in the plant bed according to the weight constrain for the analysis and the physical space needed for the growth.

5.1 Light intensity definition

After the construction of the chamber, the first step is to define the condition under which the experiment is conducted. Initially, it is necessary to measure the light intensity in different areas of the plant bed using the light sensor. In particular, the measurement is taken in nine different points, as shown in figure 5.1, in order to know more precisely the light distribution and to define the type of experiment. Additionally, in a first stage, the LEDs have been placed at three different heights from the plant bed to obtain the most favorable conditions to conduct the experiment. In a second moment, it has been noticed that the distribution of the light intensity is not uniform. Consequently, reflective panels have been installed in order to standardize and to increase the intensity of the light. The measurements has been taken with two different setup of the panels: in a first moment they has been installed only on the side along the corridor. Subsequently, they have been added on the side of the atomizer pump. In the tables 5.1, 5.2 and 5.3, the results of the light intensity measurements are reported for each height and each setup with or without the reflective panels.

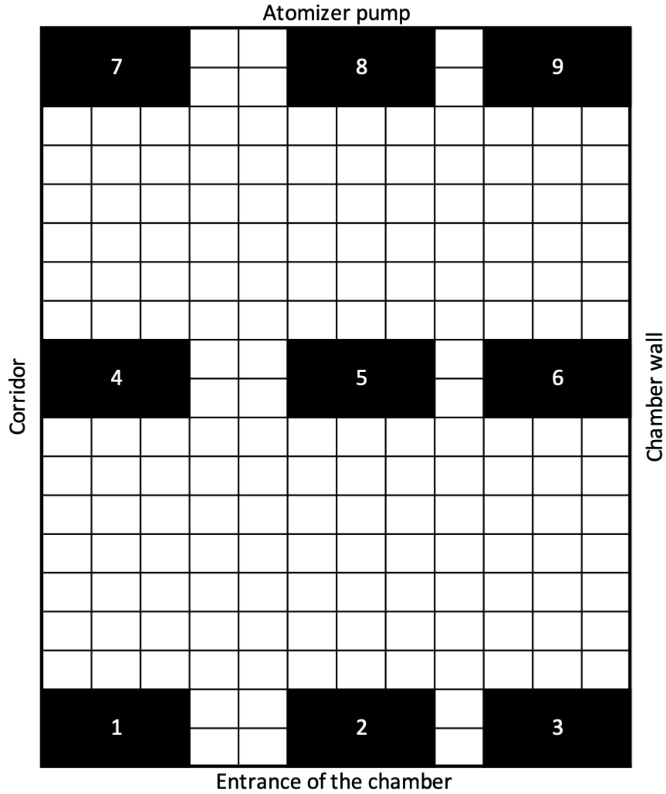

Figure 5.1: Light intensity measurement areas

Table 5.1: Light intensity measurements at 14cm height

Position	Without reflective panels	With reflective panels side corridor	With reflective panels both sides
1	288	286.1	279.3
2	292.6	284.6	287.6
3	204.3	227.1	227.9
4	320.7	310.5	307.3
5	316.2	300.1	296.9
6	216.8	238.1	218.7
7	308.8	288.1	284.1
8	287.1	262.2	265.6
9	208.2	196.2	194.7

Table 5.2: Light intensity measurements at 42cm height

Position	Without reflective panels	With reflective panels side corridor	With reflective panels both sides
1	87.4	102.7	102.8
2	104.7	111.9	113.1
3	109.8	113.2	118.7
4	105.4	123.3	122.4
5	121.7	129.8	132.1
6	127.8	130.6	134.6
7	77.1	92.2	97.4
8	94.7	100.4	96.8
9	97.5	97.6	98.1

Table 5.3: Light intensity measurements at 52cm height

Position	Without reflective panels	With reflective panels side corridor	With reflective panels both sides
1	71.5	92.9	92.3
2	80.9	93.2	96.7
3	83.9	94.6	98.4
4	77.1	100.2	107.6
5	88.3	103.1	110.4
6	91.9	103.4	111.8
7	61.8	76.8	89.9
8	71.3	81.3	94.4
9	73.8	81.4	91.7

For each measurements, in order to choose the best setup of the lights, it has been calculated the mean, the standard deviation and the difference between the maximum and minimum value of light intensity measured (Δ ppfd), with the use of the following equations:

$$Mean\ value\ (\mu) = \frac{\sum(x_{\mathrm{i}})}{N} \tag{5.1}$$

$$Standard\ deviation = \sqrt{\frac{\sum(x_{\mathrm{i}} - \mu)^2}{N}} \tag{5.2}$$

$$\Delta\ ppfd = x_{\max} - x_{\min} \tag{5.3}$$

The equations are characterized by the following values:

- x_i: it is the value of the intensity of the light in the position i;
- N: it is the total number of the positions. In this situation, it is equal to 9;
- x_{max}: it is the maximum value of the light intensity measurement in the considered condition between the all positions;
- x_{min}: it is the minimum value measured for the light intensity for the setup considered between the all values measured in the positions.

The results are reported in the following tables, 5.4, 5.5 and 5.6.

Table 5.4: Mean, standard deviation and difference maximum and minimum value of light intensity at 14cm height

Position	Without reflective panels	With reflective panels side corridor	With reflective panels both sides
Mean	271.41	265.91	262.46
Standard deviation	47.81	38.03	39.20
Δ ppfd	116.4	114.3	112.6

Table 5.5: Mean, standard deviation and difference maximum and minimum value of light intensity at 42cm height

Position	Without reflective panels	With reflective panels side corridor	With reflective panels both sides
Mean	102.9	111.3	112.89
Standard deviation	15.94	14.18	14.93
Δ ppfd	50.9	38.4	37.8

Table 5.6: Mean, standard deviation and difference maximum and minimum value of light intensity at 52cm height

Position	Without reflective panels	With reflective panels side corridor	With reflective panels both sides
Mean	77.83	91.88	99.24
Standard deviation	9.42	9.92	8.48
Δ ppfd	30.1	26.6	21.9

From the results obtained, it is shown that, at the height of 14cm, the mean value of the intensity of the light is optimal for the experiment. On the other hand, the standard deviation and the difference from the maximum and minimum value are very high because in this setup there are some peaks of intensity. Moreover, the limited height can burn some parts of the leaf during the growth of the plants. For what concern the 42cm height, the mean of the intensity is far lower than the previous setup, but this allows to obtain better value for the standard deviation and the Δ ppfd.
At 52cm height, the situation is opposite to 14cm, because the mean of the values is too small to conduce the experiment, even if the standard deviation and the difference between the maximum and minimum value are very small.
In the end, for the experiment, the height chosen is the 42cm because it permits to have acceptable values for the intensity of the light, keeping the values of standard deviation and Δ ppfd low. Moreover, it has been chosen to use the reflective panels in both sides to have higher values in each area of the plant bed, since it is not going to compromise the standard deviation and Δ ppfd values. In the figure 5.2, it is shown the plant bed with the light intensity at the 42cm height and the reflective panels in both sides, as used for the experiment.

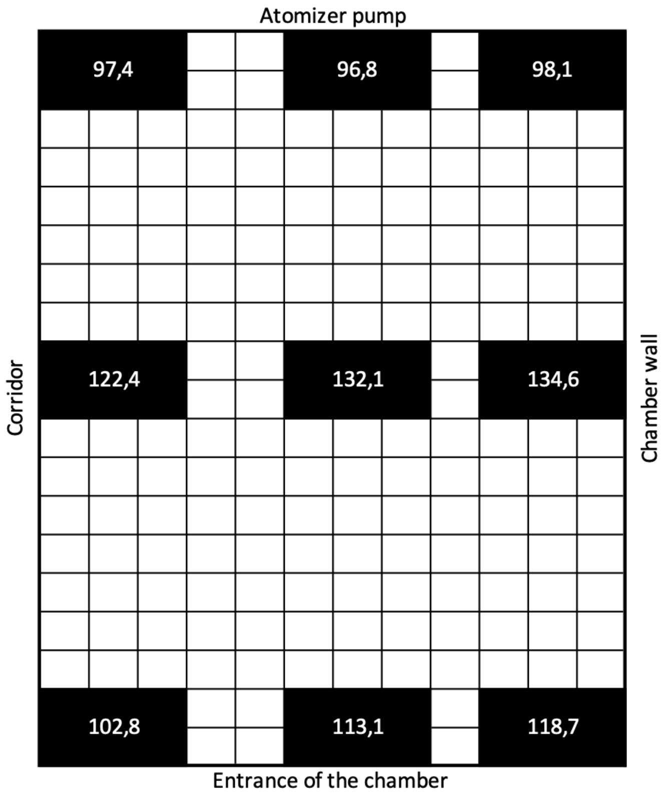

Figure 5.2: Light intensity values at 42cm with reflective panels

During the setup of the chamber, it is necessary to fix all the other parameters, for which there are the sensors, in order to optimize the growth of the plants, depending on the species. As described in the chapter 3, in the chamber analysed there are sensors for pH, electrical conductivity (EC), temperature/humidity and CO_2. Before the start of the experiment, the ranges of these variables have been set considering the characteristics needed for the development of the lettuce. Additionally, the photoperiod and the irrigation period have been defined. All the values of the variables are schematize in the table 5.7.

Table 5.7: First growing conditions

Name	Value	Units	Notes
Temperature	21-26	°C	
Humidity	55	%	
CO_2	420	ppm	Atmospheric
pH	6		
EC	1-1.6	dS m^{-1}	
Photoperiod	16	h	
Irrigation period	30	s	Every 20min

5.2 Layout of the plant bed

After the choice of the height of the LEDs and the definition of the other parameters, the following step is to decide how and where to allocate the seeds in the plant bed for the growth in order to respect the distances between them and to have the amount needed for the analysis to be performed, as described in the following section.

5.2.1 The objective of the experiment

The aim of the experiment is to analyze some characteristics of the lettuce in three different time frame during the growth of the plants. The data collected during the experiment are the followings:

1. Fresh Weight (FW): this is the weight recorded in grams when the lettuce is harvested, considering also the roots. For the first phase of the definition of the layout, since there are no data collected yet from the field, in order to understand how many plants are necessary to harvest for conducting all the measurements and for having margin, it has been considered a mean of Fresh Weight for each time span of the experiment. In particular, after the first week, the Fresh Weight considered for the lettuce, which also comprehends roots, is equal to 0.2g. For the second and the third harvesting, it is equal to 2g and 4g, respectively, as shown in table 5.8.

Table 5.8: Plant Fresh Weight for each week

Week	Grams
1	0.2
2	2
3	4

2. Dry Weight (DW): it is the weight in grams when the water content of the plant is removed. For the experiment, the DW is calculated as the 30% of the FW, reduced by the grams used for the other analysis, as shown in equation 5.4.

$$Total\ DW = [Total\ FW - (Grams\ used\ for\ the\ analysis)] \cdot 30\% \quad (5.4)$$

3. Leaf Area Index (LAI): it measures the extension of the surface of the leaves. Usually, it is measured the side facing the LEDs. The unit of measure is cm^2.
4. Number of leaves, which is expressed as the number of leaves for each plant.
5. Stem length and diameter, for which the unit of measure is, for both, cm.
6. Bacterial Load: it measures the number of bacterial present in a determined area. The unit of measure is UFC (Colony Forming Unit), which is a measure of how many cells remains viable enough to proliferate and to create small colonies. It uses the FW and it consumes 2 grams of it.
7. Nitrate (NO_3): in this analysis the concentration of the ions of nitrate is measured. The unit is measure is mol/L. This ion is, usually, present in the fertilizer because it promotes the growth of the plants. It is necessary the use of 1 gram of FW.
8. Minerals: differently from the previous, it consumes 3 grams of the DW to quantify the concentration of the minerals in the lettuce. Usually, the minerals are absorbed from the soil, but in vertical farming they are given through the nutrient solutions.

Table 5.9: Grams used for each analysis

Analysis	Grams
Bacterial Load	2
NO_3	1
Minerals	3

5.2.2 Layout 1

Due to the standard deviation and the difference between the maximum and minimum value of the intensity of light, the first layout analysed is to divide the plant bed in two different areas, uniforming the light intensity as much as possible. In the figure 5.3, it is shown how the seeds are initially placed in the plant bed, and which plants are harvested for the analysis. Particularly, where the box is not coloured, it means that the specific plant is analysed in that week. The boxes of the plant bed can be orange or blue, based on the experiment they are part of. The choice of the areas depends on the intensity of light in that zone, as shown in figure 5.2. The areas which are parts of the the blue experiment, are the positions 1, 2, 7, 8 and 9, with, respectively, the following light intensity values: 102.8, 113.1, 97.4, 96.8 and 98.1. The remaining positions are part of the orange experiment.

During the definition of the layout it is important to respect two different constraints: the first is to have enough Fresh Weight in each week for all the measurements, the second is to comply with the needed space from the lettuce for its growth in each phase. Before the definition of the layout, in order to follows the physical constrain of the lettuce, a study of the articles in the literature has been conducted. An experiment conducted in Beijing, China, has shown as after 45 days from the sewing, the lettuce has a diameter of about 13.08cm, with a FW of about 40g [7.7]. Since, the experiment conducted at the Polytechnic of Turin has the aim to analyzed the lettuce after 7, 14 and 21 days, the diameter value of the article has been reported to the weight of the plants established in the table 5.8. The value hypothesized for the diameter of the lettuce are, respectively, of 0.34cm, 3.43cm and 6.86cm, as reported in table 5.10. For understanding the distances to be maintained, the radius is considered, since the lettuce develops in all the directions, and the boxes in the plant bed have been measured, resulting about of 3cm for each side. Consequently, the choice of the layout considered these hypothetical dimensions to keep the plants far away enough. In the first week there is a distance of about 3cm, which corresponds to a box, if the plants are adjacent, instead this distance is not necessary if they are in diagonal. For the last two weeks, in which the lettuce is bigger, the minimum distance is, respectively, of 4cm and

12cm, in both situations if the empty boxes diagonally are considered, otherwise it would be greater.

Table 5.10: Physical constrain for the lettuce during the three growth phases

Week	Diameter (cm)
1	0.34
2	3.43
3	6.86

In the layout shown, the most of the plants are collected in the first week due to the lower FW of the lettuce in the initial phase, as shown in table 5.8. Consequently, in the last two weeks there are less plants, but they are more widely spaced to respect the physical constraint for the growth.

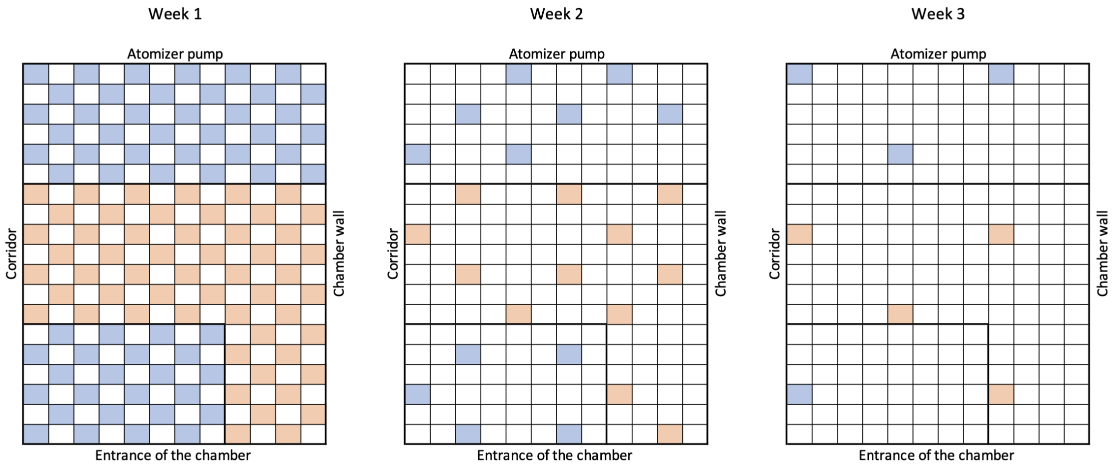

Figure 5.3: Progression of plant harvesting - Layout 1

For what concern the two different experiment, in the table 5.9 and in the table 5.11, the standard deviations and the difference between the maximum and the minimum value of light intensity are reported and they have been calculated using the equations 5.2 and 5.3. Moreover, there are the number of seeds planted, the quantity of plants used in each phase of the experiment, the quantity of grams of lettuce used for each analysis, as reported in table 5.9, and the remaining grams. The equations used for these calculations are the following:

$$Total\ FW = Number\ of\ plants \cdot Grams\ of\ plant \tag{5.5}$$

$$Total\ DW = [Total\ FW - (Bacterial\ Load + NO_3)] \cdot 30\% \tag{5.6}$$

In the equation 5.5, it is necessary to multiply the number of plants harvested in that week for the weight of the plant, as reported in the table 5.8.
As described above, the total Dry Weight is equal to the 30% of the FW, after subtracting from the FW the grams used for the analysis of bacterial load and for the nitrate. Subsequently, the 3 grams used for the analysis of the concentration of minerals in the plant are removed from the total DW, obtaining the remaining grams. It has been chosen to maintain a weight margin, because the initial weight considered for the plant is an estimate and it could be lower. Moreover, during the analysis there could occur some problems and errors, causing a loss of weight.

Table 5.11: Experiment blue - Layout 1

		Week 1	**Week 2**	**Week 3**
Standard Deviation	6.83			
Δ ppfd	16.3			
Number of seeds planted	60			
Number of plants		48	8	4
Total FW		9.6	16	16
Bacterial Load		2	2	2
NO_3		1	1	1
Total DW		1.98	3	3
Mineral		3	3	3
Grams left		-1.02	0.9	0.9

Table 5.12: Experiment orange - Layout 1

		Week 1	Week 2	Week 3
Standard Deviation	7.61			
Δ ppfd	15.9			
Number of seeds planted	54			
Number of plants		42	8	4
Total FW		8.4	16	16
Bacterial Load		2	2	2
NO_3		1	1	1
Total DW		1.62	3	3
Mineral		3	3	3
Grams left		-1.38	0.9	0.9

From the tables 5.11 and 5.12, it can be noticed that the remaining grams in both the experiment for the first week in negative. On the other hand, for the second and the third week there is a slight positive margin. It means that the number of plants is not sufficient in order to complete all the analysis considered. For this reason, the second layout studied does not consider two different experiment in the same plant bed, in order to have enough lettuce for the first week, in which the weight is very small.

5.2.3 Layout 2

A second possible layout has been developed for the experiment, in which a unique area is considered, with an higher standard deviation and an higher difference between the maximum and minimum value of light intensity. In figure 5.4, the layout with the progression of the plant harvesting during the three weeks, is shown. As for the first layout, it is necessary to respect the physical constrain for the growth of the plants, as reported in the section 5.2.2, and the weight constrain to have enough grams to calculate all the parameters of interest. In the first week the plants are smaller and they can be closer to each other, with the same positions as in the layout 1, permitting to have more grams for the measurements. In the last two weeks, the plants, being bigger, need more space for the growth, but they are heavy enough that even a few are enough for measurements. The minimum distance ensured to the lettuce in the weeks 2 and 3 is of about 6cm and 11cm, respectively.

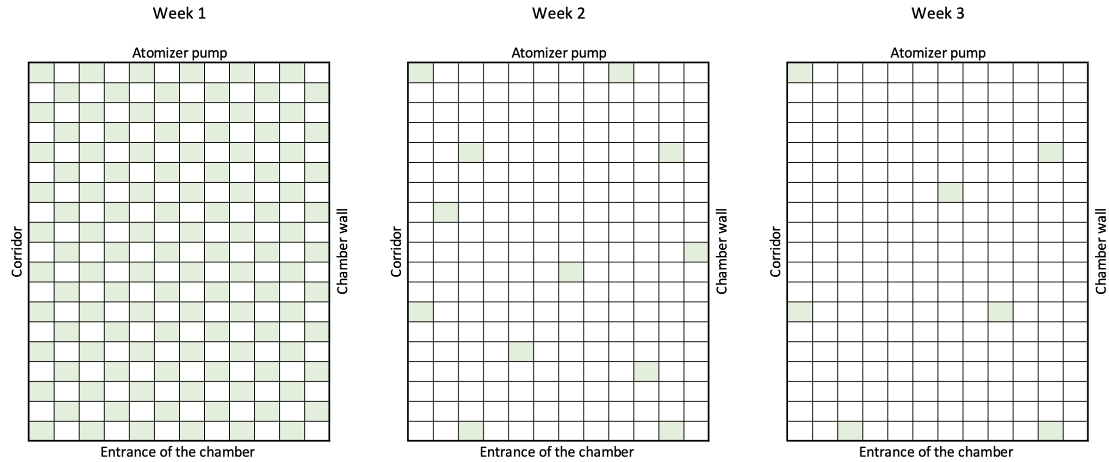

Figure 5.4: Progression of plant harvesting - Layout 2

In the table 5.13 there are reported all the values for the parameters of interest, calculated with the same equations of the first layout, in order to permit the comparison.

Table 5.13: Experiment - Layout 2

		Week 1	Week 2	Week 3
Standard Deviation	14.93			
Δ ppfd	37.8			
Number of seeds planted	114			
Number of plants		96	12	6
Total FW		19.2	24	24
Bacterial Load		2	2	2
NO_3		1	1	1
Total DW		4.86	6.3	6.3
Mineral		3	3	3
Grams left		1.86	3.3	3.3

Considering a unique experiment, it is possible to have an higher number of plants which can be analysed in the first week, guaranteeing the weight in grams necessary for all the analysis. Moreover, it also permits to have a greater margin for the subsequent weeks. On the other hand, the standard deviation is doubled because of the higher difference between the values of the light intensity.

Other possible solutions have been studied in order to optimize the results for the experiment. For the example, two other possibilities for the setup of the plant bed are characterized by the elimination of the outliers of the light intensity measurement. Specifically, one layout is determined by the elimination of the highest values of the intensity, which are the positions 5 and 6 in the figure 5.2. The second option is not to consider for the sowing the areas with the lowest values of the light intensity, which are the positions 7, 8 and 9 in the figure 5.2. In both cases, the standard deviation and the Δ ppfd obtained are not so different from the second layout analysed, in which all the areas are taken into account. Moreover, not considering some areas leads to have less number of plants, which can be analysed, resulting in a smaller margin in the remaining grams.

For all these reasons, the layout initially used for the experiment is the second one. In autumn, there is the possibility to install a second plant bed in the same chamber, permitting, consequently, to consider also the first layout on both plant beds, in order to have enough grams for the analysis.

Chapter 6

Conclusions

This thesis work had the objective of analyzing the innovative indoor cultivation method of the vertical farming, starting by describing the technique, focusing on the advantages and the disadvantages, and then analyzing the growth chamber built at the Polytechnic of Turin in order to experiment the development of lettuce. This final chapter has the objective to sum up the results and the criticality of the experiment, the limitations of the thesis and the possible future steps.

6.1 Summary of critical issues and proposed solutions

The Vertical Farming is an innovative cultivation method, which presents numerous advantages, first of all the attention to the sustainability under different contexts, but also with several difficulties to be developed.

First of all, a deep analysis on the Vertical Farming and the experiments already present in literature has been conducted. In particular, the main focus was the intensity of light, due to the difficulties to manage the growth of the plants in an indoor cultivation method. Two of the most inherent experiments found on Scopus [4.1] have been analysed more in detail because they have been a starting point for the definition of the experiment to be conducted.

The first aspect analysed during this thesis work is the IoT architecture for the system. The development of a Vertical Farming system requires the presence of an appropriate structure, composed by the sensors, which has the role of collecting the data from the field, the actuators, which provide the elements for the growth of the plants, the microprocessor, which coordinates the system, and the software used for all the layers of the IoT architecture. After the study of the architecture, an ER

Diagram has been presented. The Diagram has been developed also in order to be used in the future, when additional chambers will be added. The development of a complete database can be helpful for monitoring and managing all the parameters, which have to be set inside the chamber for the growth of the plants, and all the measurements of some important KPIs of the plants itself.

The analysis conducted on the growth chamber at the Polytechnic of Turin has underlined the difficulty to have an uniform light intensity on the whole plant bed of the aeroponic system. One of the solution proposed is to measure with an innovative sensor the light intensity on different areas of the plant bed, trying to create zones with similar values, allowing an equal distribution of the light to the plants of that surface. Moreover, the use of reflective panels has been implemented in order to uniform the light in the plant bed.

The second phase of the experiment is based on the definition of the layout with which the plants have to be sowed. Two different versions have been proposed. The first one is characterized by the division of the plant bed in two areas, joining together the zones with closer values of light intensity. This solution guarantees smaller standard deviations and difference between the maximum and the minimum value of the light intensity. On the other hand, this solution does not allow to have enough plants in grams for the conduction of all the measurements. The second layout, instead, considers the plant bed as a unique area with an higher standard deviation and difference between the maximum and the minimum value of the light intensity. This solution has been chosen because it permits to have enough plants in all the weeks of the experiment for the measurements.
Unfortunately, the results could not be analysed because during the thesis period, no lettuce seeds have been planted, due to technical problems of the growth chamber.

6.2 Limitation of the thesis

The main limitation of this thesis work is the lack of output data, obtained from the analysis of the lettuce during the three weeks considered in the experiment. Unfortunately, during the months dedicated to the thesis, the growth chamber has had numerous technical and organizational issues, delaying the planting of the lettuce. In the next weeks, the experiment should begin.

Even if the plants would have been sowed during these months, the growth cycles that could have been reported in this work may have been limited, without giving a clear idea of the results. Moreover, the complete database based on the ER

Diagram developed would not have been available for data collection and analysis anyway.

This work is based on a research work, just born, and for this reason there have been some delays due to the approval for the purchase of components necessary for carrying out the experiment.

6.3 The possible future steps

For what concern the possible future steps, the primary goal is to reach the results from the analysis of several growth cycles of the lettuce in the growth chamber. In this way, it is possible to achieve a clearer idea about the trends in the vertical farming. Moreover, it is necessary to update the database, in order to have the possibility to analyse in a more detailed way the results obtained, also using some graphs to present the values.

In the future, it is possible to add a second aeroponic system in the same growth chamber to analyse the differences during the growth process of the lettuce, varying some conditions, as the light intensity, and leaving unchanged the common conditions of the growth chamber. Also in this case, it is necessary to implement the database as described by the ER Diagram, which considers two experiments conducted in parallel.

Subsequently, it is possible to implement the system presents at the Polytechnic of Turin, trying to enlarge the project with the use of multiple growth chamber, composed by several aeroponic systems.

No other possible future steps have been identified since the project is still at an early stage and it is necessary to identify the results and the behaviour of the system with the steps described above.

Bibliography

[1.0] Gaganjor K. & Paras C. (2021), *All about Vertical Farming: A Review*, Turkish Journal of Computer and Mathematics Education.

[1.1] Chuah Y. D., et al (2019), *Implementation of smart monitoring system in vertical farming*, IOP Conference Series: Earth and Environmental Science.

[1.2] Covington, Linnea, *What Is Urban Farming*
https://www.thespruceeats.com/what-is-urban-farming-5188341

[1.3] Zimmer, Lori, *The World's First Commercial Vertical Farm Opens in Singapore*
https://inhabitat.com/the-worlds-first-commercial-vertical-farm-opens-in-singapore/

[1.4] Planet Renewed, *Indoor Farming vs. Greenhouse: What's the Difference?*
https://planetrenewed.com/indoor-farming-vs-greenhouse-whats-the-difference/

[1.5] Agritecture, *VERTICAL FARMS VS GREENHOUSES – THE FIRST CONSIDERATION: LOCATION*
https://www.agritecture.com/blog/2021/3/4/vertical-farms-vs-greenhouses-the-first-consideration-location

[1.6] Search Medium, *Vertical farming with hydroponics*
https://medium.com/@amykwilson/vertical-farming-with-hydroponics-33d689f23ea1

[1.7] iStock, *Serra per la coltivazione di insalata*
https://www.istockphoto.com/it/foto/serra-per-la-coltivazione-di-insalata-gm505307313-44569136

[1.8] Despommier D. (2010), *The Vertical Farm: Feeding the World in the 21st Century*, Picador USA.

[1.9] Birkby J. (2016), *Vertical Farming*, ATTRA Sustainable Agriculture.

[2.0] Net Sol Water, *What is Hydroponics?*
https://www.netsolwater.com/hydroponic-systems-explained.php?blog=750

[2.1] Freight Farms, *Hydroponic Farming 101*
https://www.freightfarms.com/hydroponics

[2.2] D'Anna, Cristina, *Wick System Hydroponic Gardens*
https://www.thespruce.com/hydroponic-gardens-wick-system-1939222

[2.3] D'Anna, Cristina, *Nutrient Film Technique in Hydroponic Gardens*
https://www.thespruce.com/hydroponic-gardens-nutrient-film-technique-1939220

[2.4] The Authors (2020), *Getting to the roots of aeroponic indoor farming*, New Phytologist.

[2.5] Chandra S., Khan S., Avula B., Lata H., Yang MH., Elsohly MA., Khan IA. (2014), *Assessment of total phenolic and flavonoid content, antioxidant properties, and yield of aeroponically and conventionally grown leafy vegetables and fruit crops: a comparative study*, Evidence-based Complementary and Alternative Medicine.

[2.6] Chang DC., Park CS., Kim SY., Lee YB. (2012), *Growth and tuberization of hydroponically grown potatoes*, Potato Research 55.

[2.7] Ritter E., Angulo B., Riga P., Herràn C., Relloso J., San Jose M. (2001), *Comparison of hydroponic and aeroponic systems for the production of potato minitubers*, Potato Research 44.

[2.8] Ragnheidur I. Thorarinsdottir (2015), *Aquaponics guidelines*, Haskolaprent, Reykjavik, Iceland.

[2.9] youmatter, *What Is The Aquaponics System? Definition, Benefits, Weaknesses*
https://youmatter.world/en/definition/aquaponics-sustainable-benefits-system/

[3.0] The Plant, *Research and Production Facility Demonstrating Models for Energy Efficiency*
https://www.insidetheplant.com

[3.1] Crop Box, *Crop Box*
https://www.cropbox.com

[3.2] Growtainer, *The Portable Production Facility of the Future*
https://growtainers.com

[3.3] Brooklyn Grange, *About Brooklyn Grange*
https://www.brooklyngrangefarm.com/about

[3.4] Sky Greens, *The World's First Proven Vertical Farming Technology Sold since 2009*
https://skygreenscanada.com

[3.5] Tan, Audrey, *The world's largest vertical garden? It's right here in Singapore*
https://www.straitstimes.com/singapore/environment/the-worlds-largest-vertical-garden-its-right-here-in-singapore

[3.6] Clemson, *Ion Movement in Soil and Root Absorption*
https://www.clemson.edu/public/regulatory/ag-srvc-lab/soil-testing/pdf/ion-movement.pdf

[3.7] Dol sensors, *Sensors in vertical farming*
https://www.dol-sensors.com/sensors-in-vertical-farming/

[3.8] Nguyen K., Cho M., Lee H. Y., Cho D. Y., Lee G. O., Jang S. N., Lee Y., Kim D., Son K, (2021), *Effects of White LED Lighting with Specific Shorter Blue and/or Green Wavelength on the Growth and Quality of Two Lettuce Cultivars in a Vertical Farming System*, Agronomy.

[3.9] Ragaveena S., Shirly Edward A., Surendran U. (2021), *Smart controlled environment agriculture methods: a holist review*, Springer.

[4.0] VoltGrow, *What Is The Best Light Spectrum For Plant Growth?*
https://www.voltlighting.com/grow/best-light-spectrum-plant-growth#: :text=The%20spectrum%20of%20light%20that,plants%20and%20

utilized%20for%20growth.

[4.1] Scopus, *Sources*
https://www.scopus.com/search/form.uri?zone=TopNavBar&origin=sbrowse&display=basic#basic

[4.2] AydinLatma Portali, *What Are PAR, PPF and PPFD?*
https://www.aydinlatma.org/en/what-are-par-ppf-and-ppfd.html

[4.3] Pennisi G., Sanyè-Mengual E., Orsini F., Crepaldi A., Nicola S., Ochoa J., Fernandez J. A., Gianquinto G., (2019), *Modelling Environmental Burdens of Indoor-Grown Vegetables and Herbs as Affected by Red and Blue LED lighting*, Sustainability.

[4.4] Smart Factory, (2022), *METTIAMO IN CAMPO AGRICOLTURA 4.0*, Smart Factory, Tecnologia & Innovazione, December 2022, pp. 140-142.

[4.5] Technophylla, *Technophylla, Digital Farming 4.0: Digital Solutions For Modern, Efficient And Sustainable Agriculture*
https://www.technophylla.eu

[4.6] Oracle, *What is IoT?*
https://www.oracle.com/internet-of-things/what-is-iot/

[4.7] Velazquez, Rosa, *IoT: The Internet of Things. What Is the Internet of Things? How Does IoT Work?*
https://builtin.com/internet-things

[4.8] Blog Osservatori, *INTERNET of THINGS (IoT). Significato, esempi, ambiti applicativi e prospettive di mercato in Italia*
https://blog.osservatori.net/it_it/cos-e-internet-of-things

[4.9] Innovation insider, *8 Sectors That Can Benefit the Most from IoT Development in 2023*
https://imaginovation.net/blog/8-sectors-benefit-from-iot-development-in-2021/

[5.0] HelpWire, *Complete Guide to loT Smart Home*
https://www.helpwire.app/blog/iot-smart-home/

[5.1] DataFlair, *How IoT Works – 4 Main Components of IoT System*
https://data-flair.training/blogs/how-iot-works/

[5.2] Baianat, *How IoT is Transforming Industries?*
https://www.baianat.com/articles/how-iot-is-transforming-industries

[5.3] Eisner, Caroline, *What Is ISA-95?*
https://www.getmaintainx.com/learning-center/what-is-isa-95/

[5.4] Lachance, Paul, *An Introduction to IoT, CMMS and the ISA-95 Framework*
https://www.brightlysoftware.com/blog/introduction-iot-cmms-and-isa-95-framework

[5.5] Fasciolo B., Awouda A., Bruno G., Lombardi F., (2023),*A smart aeroponic system for sustainable indoor farming*, Elsevier.

[5.6] Valdez, Jonathan & Becker, Jared, *Understanding the I2C Bus*
https://www.ti.com/lit/an/slva704/slva704.pdf?ts=1689727965469&ref_url=https%253A%2

[5.7] Atlas Scientific, *pH Kit*
https://atlas-scientific.com/kits/ph-kit/

[5.8] Atlas Scientific, *Basic EZO™ Inline Voltage Isolator*
https://atlas-scientific.com/ezo-accessories/basic-ezo-inline-voltage-isolator/

[5.9] Atlas Scientific, *Mini Conductivity K 1.0 Kit*
https://atlas-scientific.com/kits/mini-conductivity-k-1-0-kit/

[6.0] Atlas Scientific, *EZO-CO2™ Embedded Carbon Dioxide Sensor*
https://atlas-scientific.com/probes/co2-sensor/

[6.1] Apogee Instrument, *MQ-500: Full-Spectrum Quantum Meter*
https://www.apogeeinstruments.com/mq-500-full-spectrum-quantum-meter/#product-tab-description

[6.2] Adafruit, *SHT-30 Mesh-protected Weather-proof Temperature/Humidity Sensor - 1M Cable*
https://www.adafruit.com/product/4099

[6.3] Debem Industrial Pumps, *Cosa sono le pompe peristaltiche e come funzionano?*
https://www.debem.com/it/cosa-sono-le-pompe-peristaltiche/

[6.4] Atlas Scientific, *EZO-PMP Embedded Dosing Pump*
https://atlas-scientific.com/peristaltic/ezo-pmp/

[6.5] SunFounder, *5V 8 Channel Relay Shield Module for Raspberry Pi /Arduino*
https://www.sunfounder.com/products/8channel-relay-shield

[6.6] AliExpress, *BF-4800 diretta Della Fabbrica 80 W ad alta pressione pompa di lavaggio auto pompa a diaframma DC 12 V pompa booster*
https://it.aliexpress.com/item/32966789754.html?gatewayAdapt=glo2ita

[6.7] Elmo s.r.l, *Led*
https://www.elmosrl.com/products.html

[6.8] Idroponica.it, *VENTILATORE OSCILLANTE 18CM A 2 VELOCITÀ 20W - RAM*
https://www.idroponica.it/ventilatore-oscillante-18cm-a-2-velocit-20w-ram 49803.html

[6.9] Raspberry Pi, *Raspberry Pi hardware*
https://www.raspberrypi.com/documentation/computers/raspberry-pi.html

[7.0] Gadget Versus, *Broadcom BCM2711 Processor Benchmarks and Specs*
https://gadgetversus.com/processor/broadcom-bcm2711-specs/

[7.1] Node-RED, *Node-RED Low-code programming for event-driven applications*
https://nodered.org

[7.2] Mosquitto, *Eclipse Mosquitto An open source MQTT broker*
https://mosquitto.org

[7.3] PostgreSQL, *About PostgreSQL*
https://www.postgresql.org/about/

[7.4] Idroponica.it, *MAMMOTH CLASSIC150 + GROW BOX INDOOR*
https://www.idroponica.it/mammoth-classic150–150x150x200cm-grow-box 23142.html

[7.5] LucidChart, *What is an Entity Relationship Diagram (ERD)?*
https://www.lucidchart.com/pages/er-diagrams

[7.6] SMARTDRAW, *Entity Relationship Diagram (ERD)* https://www.smartdraw.com/entity-relationship-diagram/

[7.7] LI Q., LI X., TANG B., GU M., (2018), *Growth Responses and Root Characteristics of the Lettuce Grown in Aeroponics, Hydroponics, and Substrate Culture*, Horticulturae.