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A smart aeroponic system for sustainable indoor farming

Benedetta Fasciolo[a]*, Ahmed Awouda[a], Giulia Bruno[a], Franco Lombardi[a]

[a]Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy

* Benedetta Fasciolo. Tel.: +393773167760; *E-mail address:* benedetta.fasciolo@polito.it

Abstract

Population growth requires a significant increase in agricultural production to ensure food security. However, the further increase in such production is limited by the environmental crises and by the negative impacts of open-field agricultural practices. Vertical farming techniques, such as aeroponics, can be exploited to optimize the use of resources. This paper presents a methodology for developing a smart aeroponic systems, based on IoT and artificial intelligence algorithms. The proposed methodology is used to identify the parameters that affect plant growth and their correlations with the plant performance indicators. The obtained smart aeroponic system will be able to automatically balance resource utilization (e.g., water, nutrients, energy) and crop productivity.

Keywords: vertical farming; indoor farming; aeroponic; crop growth procedure; IoT; AI algorithms.

1. Introduction

The world population could grow to about 8.5 billion in 2030, and add 1.18 billion in the next two decades, reaching 9.7 billion in 2050 [25]. Moreover, the world is expected to be more than two-thirds urban (68 percent) by 2050 [26]. Therefore, a significant increase in agricultural production will be required in the coming decades to ensure food security. However, there are two main threats: growing urbanization and the environmental crisis.

Climate change strongly impacts plant abiotic stresses such as temperature, heavy metals, salinity, etc. The increase of CO_2 in the atmosphere brings a higher plant growth rate due to raised photosynthesis efficiency. However, greenhouse gases also lead to increased temperatures that offset the beneficial effect on yield productivity due to heat stress and reduced availability of water [15]. The higher temperatures also lead to the denaturation of the microbial population present in the soil. Moreover, soil salinity has been accentuated by climate change. This turns out to be one of the stresses with the greatest relevance because the extent of the area affected by salinity is expected to cover about 50 percent of the total agricultural land by 2050 [12]. Finally, due to the current climate crisis, resource availability is limited. As for agriculture, there are shortages of macro and micronutrients, such as phosphorus and nitrogen.

As climate change has an impact on agriculture, also cultivation activities influence the environmental crisis. Due to deforestation and intensive agricultural activity, a large amount of CO_2 has been released into the environment. Moreover, the conversion of natural ecosystems to agricultural ones increases soil temperature and reduces soil moisture in the root zone.

Another agricultural activity that significantly impacts the environment is the use of fertilizers and phytosanitary products. The utilization of these chemicals is essential to provide plants with the necessary nutrients and protect them from pests. However, their use and production cause water and air pollution [1]. In addition, the use of pesticides results in a loss of biodiversity. Lastly, several agricultural methods impact the environment and agricultural efficiency. For example, the continuous cropping (CC) technique has led to decreased rhizosphere soil pH, nutrient imbalance, and reduced enzyme activity. All the effects described above vary their impact

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depending on the type of crop, the type of soil, and generally the climatic conditions.
The influence that agriculture has on the environmental crisis and vice versa are significant and it strongly threatens food security and the ecosystem. To break this loop is important to act using sustainable agricultural techniques. Today, several methods have been developed to mitigate some of the impacts described above. This paper is focused on a specific sustainable agriculture system: vertical farming. In recent years, several papers have been published describing vertical farming and comparing them to traditional agriculture. Moreover, there are some works on the integration of IoT and AI networks into these systems. However, there is not a deep investigation of smart solutions for vertical farming, since most of the systems are still classified as prototypes. Thus, new research opportunities are present in this field to investigate how these integrated systems can be optimized to improve vertical farming performances. This paper presents a methodology based on IoT and AI to identify the parameters that affect plant growth and their correlations with the plant performance indicators, with the final aim of improving crop productivity.
The present work is structured as follows. Section 2 describes the types of vertical farming, their integration with the AI and IoT network, and their advantages and challenges. Section 3 describes the proposed methodology. Section 4 describes the IoT architecture needed to implement the proposed methodology. Finally, Section 5 concludes the paper and presents future developments.

2. Smart Indoor Farming

Indoor farming is divided into two major areas: greenhouse and vertical farming. Vertical farming mainly includes techniques such as hydroponics, aquaponics, aeroponics, and bioponics. Hydroponics is a technique to grow plants without soil that is replaced with a growing media, adding nutrients or fertilizers into a nutrient solution. Hydroponic techniques are divided into open systems, where the excess nutrient solution is not recycled, and closed systems, where the nutrient solution from the root is recycled and replenished [19]. Aeroponics is a method of growing plants without the use of growing media. Indeed, the nutrient solution is nebulized onto the plant's roots [3]. Aquaponics is a growing method whereby plants and fish are grown together and the waste from the fish is used as fertilizer for the plants. Lastly, bioponics is a combination of aquaponics and hydroponics. The nutrients, released by the biological activity of microorganisms, are derived from multiple sources such as natural substances of plant, animal, and mineral origin [19].

2.1 Aeroponic system

As shown in Figure 1, the aeroponic technique exposes the plant roots to aerosol droplets that contain the nutrient solution. In nature, there are plants such as epiphytic orchids and bromeliads living in an aeroponic system by collecting nutrients from mist through the leaves and root surfaces. A common technique is high-pressure atomization where a high-pressure nutrient solution is forced through an orifice turning the liquid into droplets. This method generates 10-100μm diameter droplets [3].

The aeroponic structure consists of a tank where plant roots are placed close to nozzles and pipes that recover or supply the nutrient solution. The whole system is contained within a thermally insulated chamber.
The main actuators are as follows:

- pumps and nozzles that provide the nutrient solution to the roots;
- LED lights that provide artificial lighting to the plants;
- air conditioning system and fans to regulate air circulation, temperature, and humidity;
- piping system for nutrient solution recovery.

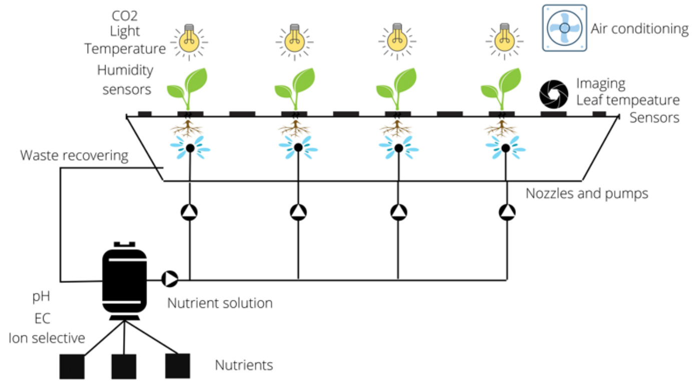

Fig. 1. Aeroponic system

Aeroponics is thought to solve several plant physiological constraints occurring during hydroponic cultivation. This can include greater oxygen availability within the root bed and enhanced water use efficiency. However, it also requires more extensive farm infrastructure and actuators compared with mature hydroponics technologies. In addition, more studies need to be done on the type of nozzle used, size of drop emitted, frequency of irrigation, and pressure of the nutrient solution. [2,22].

2.2 IoT and AI in vertical farming

To make vertical farming more efficient and ensure less environmental impact, it is important to integrate it to IoT and AI. In an agricultural controlled environment, the system acquires data on plant physiology and growth through sensors. Then, these data can be analyzed by artificial intelligence algorithms to monitor plant development by optimizing resources [19]. The implementation of IoT is already deployed and applied in vertical farming systems and in recent years it has been integrated with AI to monitor plant growth.
Types of problems that are handled by AI in vertical farming are generally categorized into prediction and control or optimization problems. Regarding prediction, models such as Support Vector Regression (SVR) have been used to forecast optimum harvesting time and predict accurate crop yields [5]. Other works proved that instead of using separately SVM, Multiple Linear Regression (MLR) and Artificial Neural Networks (ANN) to predict crop yields, it is better to use an integrated approach [7]. Moreover, Random Forest Regression has been used to predict the threshold values of PH and other parameters [16]. Regarding control and optimization, Random Forest Classification has been used to optimize the control function of grow lights [10], and Deep Neural Networks has been used to provide control action for a hydroponic

environment in real time, such as controlling sprinkler and water flow based on PH, temperature, humidity, and water flowrate [21].
Among the benefits of using AI techniques there is the elimination of the uncertainty associated with judging plant health by human opinion, and the use of resources more precisely, reducing production-related waste and pollution. [4]. On the other hand, it is also known that when data are scarce or of poor quality, AI has limitations [4]. Inaccurate data can be generated by sensors that have been degraded by the environment, while the quality of images captured by cameras and videos is affected by low light, weather, obstruction by insects or plants, and cloudy lenses [23]. Unreliable sensing, processing, and transmission can lead to erroneous monitoring data reports, long delays, and even data loss, thus ultimately impacting the model results [22]. Also, standardization is needed to take full advantage of digital technology [22]. Lastly, systems that are powered by IoT and AI are also very expensive, since they need deployment, operation, and maintenance activities [22].

2.3 Advantages and challenges

The use of vertical farming techniques for plant production can bring several advantages and mitigate some previously described effects that affect the quality and productivity of open-field agriculture.

Table 1 Consumption for lettuce production in different agricultural systems

	Vertical farming	Greenhouse	Open-field	Reference
Water [g/L]	45-80	5-60	3-20	[17]
Land [g/m2d]	1300-3000	100-300	10-15	[2]
Energy [kWh/kg]	13.3	9	0.5	[17]

Table 1. summarizes the three main indicators used to evaluate the benefits and drawbacks of vertical farming compared with the alternative systems (open-field and greenhouse). By analyzing water and land consumption, vertical farming performs significantly better than greenhouse and open-field agriculture. On the other hand, the energy consumption of vertical farming is usually higher than the other systems.
The high performance on water consumption is because in vertical farms the efficiency of water use is over 0.95, while in a greenhouse it is about 0.02 [24]. This high efficiency is due to an optimized use of water during crop growth and the avoidance of it washing crops before eating to remove pesticides, insects, and foreign particles [1, 24].
The high performance on land exploitation is due to vertical space optimization. Soil fertility is one of the main requirements of crop production in the open field. However, up to 33% of global soils have reduced or lost fertility due to degradation processes caused by unsustainable soil management practices [6]. Moreover, the world is expected to be more than two-thirds urban by 2050, turning a large amount of soil into urban areas [26].
The main drawback of vertical farming is the fact that the energy consumption is usually higher than greenhouses and open fields. A way to reduce energy consumption is to optimize the lighting system, which is responsible for 50% of the energy costs [1]. Moreover, by using renewable energy sources, the environmental impact can be reduced [20]. To reduce the energy requirements, works suggest using optimized LEDs and identifying the optimal light spectrum [11]. Finally, concentrating crop production in the less cold season could reduce emissions and energy costs due to their seasonal dependence.
In addition to these three indicators, other factors (e.g., pesticide use, food transportation) are analyzed in the literature, even if there is no clear comparison of values among the three systems. Over the past three decades, the average annual consumption of pesticides has been 1.58 kg per hectare, corresponding to 0.37 kg per person. [6]. In vertical farming systems, a reduction or zeroing of pesticide application is present in most cases because it is a closed and monitored environment where the occurrence of pathogens is minimized, and the amount of nutrition supplied to the plant is optimized. [1, 3]. The possibility of building vertical farming systems near urban areas drastically decreases the food miles and the food losses that occur in the supply chain. It has been estimated that vegetable and fruit loss in the world is around 40-50% of the total production [1]. In addition, transportation accounts for 19% of total food-system emissions. 36% of such emissions correspond to the emissions for the transportation of fruits and vegetables, which is almost double the emissions produced during their yielding [14].
Thus, vertical farming is a system that has several advantages and some disadvantages compared to traditional agriculture. However, there are studies in the literature that propose strategies to reduce the main impacts of vertical farming such as energy [11].

3. Proposed methodology

The proposed methodology aims at defining a crop growth procedure to optimize performances in an aeroponic system, whereby crop growth procedure we mean a recipe that indicates the optimal values of input parameters to achieve the desired values of the plant performance indicators. The methodology is divided in three phases, as shown in Figure 2, accordingly to the IDEF0 formalism [13].

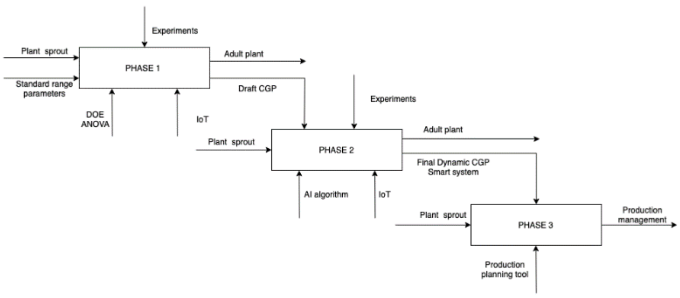

Fig. 2. Proposed methodology

Such phases are repeated for each stage of plant growth that occurs within the soilless system (seedling and adult plant). For each phase, the arrows entering from the left side represent the inputs of the phase, the arrows exiting from the right side represent the outputs, the incoming arrows from the upper side represent the controls used to implement the phase, and the incoming arrows from the lower side represent the resources used. Each phase is described in details in the following paragraphs.

3.1 First phase

In the first phase, the cause-and-effect relationships between the inputs provided by the system and the output that is the growth of the plant is studied. Two analyses are done. The first one is on the primary and essential parameters for plant development such as nutrients, water, light, temperature, etc. The second one is on the secondary parameters that mainly include the structure of the aeroponic system such as nozzle size, nutrient pressure, and droplet size.
Several experiments are carried out on a specific type of crop in the aeroponic system by changing the input values and measuring the plant's response.
Once the type of crops has been selected, the seeds need to complete the sprouting phase inside a dark chamber. Then, the plant is moved to the aeroponic system where it continues its growth. The vertical farming system is characterized by several parallel chambers where different experiments are carried out simultaneously. In fact, in each compartment, input parameters change through actuators and the plant's response is measured. The selection of input, its ranges, and the choice of output, are done according to the DOE. Specifically, the composition of the nutrient solution, temperature, light intensity, and humidity will be varied as inputs. Instead, the leaf's area, volume, color, and temperature will be measured as outputs. Then, statistical analyses are done to identify cause-and-effect relationships between the inputs and outputs of the system. Indeed, the significance of input variables and their interaction will be obtained using DOE and ANOVA. Through these two analyses, optimal input values will be obtained. This study is repeated when the plant moves to the adult stage. Once the growth cycle is finished, new experiments start on the crop, and secondary parameters including nozzle size, nutrient pressure, and droplet size are studied as inputs.
At the end of the first step, there is a deeper understanding of the cause-effect relationships between plant growth and primary-secondary parameters. Moreover, an initial crop growth procedure is created to get the basic parameters for the implementation of the second phase.

3.2 Second phase

The second phase takes as input the correlations among input parameters and plant growth indicators found in the first phase, and the new experiments done in a more extended set of conditions. These data are used to feed AI algorithms and derive models to develop a specific crop growth procedure, needed to monitor crop growth and evaluate plant health. Based on similar works found in literature, we plan to apply different AI algorithms (e.g., SVM, MLR, ANN) to compare the results and select the model that reaches the highest accuracy. We also plan to develop integrated or hybrid models in order to combine different approaches. The added value of AI in this phase is the ability to obtain accurate models that describe plant growth based on the input parameters provided by the cultivation system. In addition, the implementation of AI makes it possible to obtain a dynamic model that becomes more accurate over time as the amount of data provided increases. On the other hand, to build an accurate model, a careful analysis of the size and reliability of the dataset is needed.

3.3 Third phase

The last step of the study includes production planning according to the demand. Crop production in aeroponic systems should follow a just-in-time logic. This is essential to ensure good product quality and avoid food waste. This happens when the production is off-season as the crop, once out of the aeroponic system, could quickly deteriorate due to hostile climatic conditions. Therefore, with the specific crop growth procedure obtained from the previous phases, the production can be scheduled according to demand minimizing waste and resources through a production planning tool.

4. IoT architecture design

To support the implementation of the proposed methodology, an IoT architecture has been designed, as shown in Figure 3. The designed architecture is a 4-layer model consisting of a Field layer, an Edge & Controller layer, a Platform layer, and an Application layer. In the following paragraphs, the layers are described in detail, and also the functions supported by the architecture.

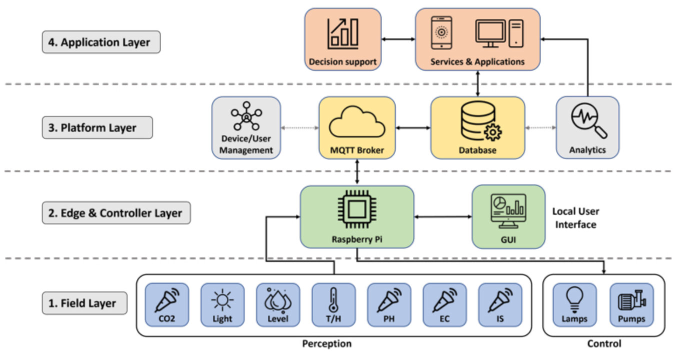

Fig. 3. IoT architecture

4.1 Layers

4.1.1 Device Layer

The device layer contains physical devices that interact directly with the environment. These devices include sensors, pumps, and other actuators. The components in this layer are responsible for gathering data from the aeroponics system and forwarding it to the next layer for further processing. As seen in Table 2, various sensors and actuators have been selected. Based on the sensed parameters and controlled variables these sensors can be divided into nutrient (Ph, EC, Ion selective & level), climatic (temperature, humidity, CO_2) and environmental sensors (PAR sensor).

4.1.2 Edge & Controller Layer

This layer is responsible for receiving and processing all the field data received by the sensors. It provides control actions to the actuators, to achieve automatic control of the aeroponic system. In addition to control, also edge computations are done here.
In the proposed system a raspberry pi and a local user interface

are included. Raspberry Pi is a single board micro computer running on open-source software that contains an I/O terminal to allow the connection of sensors, actuators, and other peripherals [27]. It is the main controller and gateway in the system in addition to working as a server for the web-based GUI. Raspberry pi has been selected for its ability to run open-source software and supports many communication protocols [18].
All the functions of the Raspberry pi can be programmed by using Node-red [9]. Node-Red is a flow based open-source programming tool built upon Node.js, which is used to connect hardware devices, API's and other online services belonging to the realm of IoT. One of the biggest advantages of Node-Red is its ability to run at the edge of the network on low-cost hardware such as the Raspberry Pi.
The protocols used for low level communication used to extract sensor data from the field layer are I2C, SPI and Modbus [18]. The high level or IP based communication protocol used to communicate with the platform layer is MQTT, a lightweight publish-subscribe network protocol that transmits messages between devices, systems and cloud platforms [8].

Table 2: Sensors & actuators used in the aeroponic system

	Type	Description
SENSORS	PH	Measures hydrogen ions present in the nutrient solution, optimal range 5.5-6.5 PH
	Electrical Conductivity	Measures the total dissolved salts present in the solution, which influences a plant's ability to absorb water, it is an indicator of water quality & salinity, optimal range 1.5-2.5 dS m-1
	Ion Selective	Measures the individual ion activity, ion activity is the effective concentration of a given salt in the solution
	Level	Measures the level of Nutrient solution in the reservoir
	Temperature/ Humidity	Measures Temperature and relative humidity in the chamber
	Full Spectrum PAR Sensor	Detects the amount of incident light falling on the plants in the aeroponics chamber, measures PPFD which is the number of photons reaching the leaf surface
	CO_2	Measures the amount of CO_2 in the chamber which influences the photosynthesis efficiency
ACTUATORS	Pumps	4 Pumps in system, Main pump for taking the nutrient solution to the plant roots, 3 peristaltic pumps for nutrient dosing
	Grow Lamps	Essential for plant photosynthesis, 2 LED lamps are present, Blue spectra for plant growth during vegetative state, Red spectra for flowering and blooming stage

4.1.3 Platform Layer

This layer handles communication, storage, analytics in addition to user and device management. Several IoT cloud platforms can be used for these functions such as ThingsSpeak, AWS & Azure. Huge amounts of data and heavy computation processes are present here therefore technologies DB management, cloud computing and machine learning are employed.
In the proposed design the platform layer consists of an MQTT broker and a data repository. An MQTT broker is a program that manages messages between MQTT clients which are divided into publishers & subscribers. Publishers are devices that generate data such as sensors and a DB that is being queried for data. Subscribers are data consumers such as actuators a DB while data is being pushed to it. The broker classifies messages into topics and send them only to subscribers interested in those topics, it is the central communication hub.

4.1.4 Application Layer

The application layer hosts the offered applications and services, this layer takes the services to the end-users, who are farmers in this case. Information, prediction, and analysis reports are shared with the farmers. Various applications that handle environment, nutrient, health, and production management are provided in this layer. These applications can be desktop based, mobile based or web based, furthermore these applications integrate with other systems and applications at the platform layer and enable Inter application data exchange. This layer assists the end user in providing decision support for aeroponics system.

4.2 Functions Supported

The designed architecture will allow (i) the collection of real-time data from various devices using different technologies and protocols of data transmission which in turn grants higher flexibility and allows a higher degree of control, (ii) the remote monitoring of processes and sensor data, and (iii) the autonomous operation of the aeroponics system under optimal growth conditions
By providing these functions the system can manage various aspects of the aeroponics system such as nutrition management, environment control and climate monitoring. Nutrition management is achieved by providing the correct amount of nutrients and delivered at the right time to the plant. PH, electrical conductivity, and ion selective sensors provide values for nutrient solution concentration. This value can be maintained at a certain threshold via feedback control using pumps that inject the correct amount of minerals to the solution. Furthermore, when the desired nutrient parameters in the solution are achieved, the system operates the main pump to transfer the obtained solution to the plants via the atomization nozzles. The autonomous operation of nutrient dosing and irrigation is maintained by the system for the duration of the plant growth. A water level sensor is also present in the nutrient solution reservoir, to read the level of the solution and inform the user if the solution falls below a specified value.
Another aspect is environmental control, especially related to the incident lighting. Light is essential for plant growth as it is needed for photosynthesis. Different light spectrums are required during different growth stages (mainly red and blue). Depending on the growth stage, time of day and external light, the system will be able to manage the artificial lighting (provided by LED lamps) by controlling light intensity, frequency of luminance and the combination of colours required.
Climate monitoring is achieved by measuring the temperature and humidity of the aeroponic system. Using the installed sensors, the user can continuously monitor the current temperature and humidity values and perform the appropriate actions if they fall out of the optimal range.

5. Conclusion

Vertical farming systems can partially mitigate the harvesting environmental impacts. For instance, vertical farming performs significantly better than greenhouse and open-field agriculture in water and land consumption. On the other hand, energy consumption is usually higher than in the traditional agriculture system. From the literature review it was found that there is not a deep investigation of smart solutions for vertical farming since most of the systems are still classified as prototypes. Thus, this work tries to investigate and study indoor food crop production using smart and intelligent techniques. Indeed, the current work offers a methodology for creating intelligent aeroponic systems based on IoT and AI algorithms. The elements that influence plant growth and their relationships to the plant performance indicators are found using the suggested methodology. Therefore, the developed smart aeroponic system will be able to automatically balance crop productivity and resource use (such as water, nutrients, and energy).

Vertical farming can be a viable alternative to traditional systems, even if it requires greater energy. For this reason, a deeper analysis is needed to identify solutions to reduce energy consumption. In addition, vertical farming needs larger investment and knowledge than open-field agriculture. Because of this, it is important to carry out also a socio-economic analysis to see if this technique can integrate current crop production.

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