Journal of Engineering Science and Technology Review 17 (1) (2024) 206 - 212

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Development and Characterisation of a Telemetry Infrastructure to Study Environmental Factors in a Custom Built Aquaponics System

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Received 24 March 2023; Accepted 8 November 2023

Abstract

This article discusses the challenges faced by the food sector, such as overexploitation of resources, climate change, and pollution, which have led to poverty and hunger in many parts of the world. The United Nations' Sustainable Development Goals (SDGs) call for responsible production and consumption, as well as zero hunger, to be achieved within 15 years. One solution to achieve these goals is aquaponics, a system that integrates aquaculture and hydroponics, which has several advantages such as pesticide-free products, efficient use of water, decreased pollution and eutrophication, and higher vegetable production per m2. The article focuses on the dynamics of nutrients in the aquaponic system, specifically how nutrients are consumed, metabolized, and released into the system, and how they are processed by bacteria and assimilated by plants. The article also discusses how technological solutions such as telemetry and the Internet of Things (IoT) can be used to improve the efficiency of aquaponic systems. Overall, the article emphasizes the importance of sustainable food production and the potential of aquaponics as a solution to achieve the SDGs.

Keywords: Aquaponics System, Telemetry

1. Introduction

Worldwide, there is a decrease and affectation of the food sector due to the overexploitation of resources, which brings poverty and hunger to the population. Pollution, decrease in the availability of water resources, soil sterility, the growth of industry, urbanization and the excessive use of agrochemicals (fertilizers, herbicides, pesticides and fungicides) have caused agriculture to rethink the methods of cultivation and food production [1]. On the other hand, climate change has brought consequences such as droughts, extreme temperatures and floods that have caused global crop losses [1]. Finally, the commercialization of food products such as fish and vegetables have been presenting high contents of metalloids and pesticides that affect people's health and therefore food safety [2]. As a result of this problem, in 2015 the Millennium Development of the United Nations (UN) proposed 17 goals to be achieved over the next 15 years, known as the Sustainable Development Goals (SDGs), among the most relevant for the development of this project are "responsible production and consumption" and "zero hunger" as one of the goals to be achieved. Among the fields of action that facilitate the fulfillment of these goals is the agricultural sector, seeking sustainable food production, ensuring food security by implementing strategies and tools that allow the integration of different technologies that optimize production systems. Aquaponic systems are a viable alternative that consists of the integration of aquaculture, for the production mainly of fish, with hydroponics in closed recirculation. [3]. In aquaponics, manure and uneaten food are used as liquid fertilizer for the plants, which in turn filter and purify the water so that these unused nutrients do not generate contamination and dirt in the fish tank [4]. The technique allows fish and plants to be raised at high density at the same time, efficient use of water through proper parameters within the system and vegetables are produced organically and cost-effectively [5].

Production in these systems has great advantages, among which are:
Generate pesticide-free products from the implementation of integrated pest management [6].

Decrease the use of synthetic chemical fertilizers required by plants, due to the use of nutrients generated in the system by the decomposition of uneaten food and feces; ionic excretion and excretion of nitrogen products by fish, and the nitrification process of bacteria [3].

Decrease pollution and eutrophication in aquatic ecosystems by excessive use of fertilizers in the agricultural area and by the reduction of wastewater generated in aquaculture systems [7].

Increase the efficiency of land use, since these systems can be built in urban areas and in places where land is limited or of poor quality, and also the production of vegetables per m2 can be higher compared to traditional crops [7].

Increase the efficiency of water use (almost 90%), through recycling and reduced recharge, due to the fact that the plants take advantage of the nutrients accumulated in the system.

In the investigation and improvement of the productivity of the systems, the dynamics of nutrients in the system is one of the topics of interest of the present project. The origin of the nutrients consumed, metabolized and released to the system comes from the feed supplied to the fish and the water used for recirculation between the fish tank and the hydroponic bed. The uneaten feed and the excretion of feces by the fish generate three types of solids in the water:

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ISSN: 1791-2377
doi:10.25103/jestr.171.24

dissolved, suspended and sedimentable, which pass by gravity to the filtration units (mechanical and biological), where solid particles are removed and converted into elements that can be used nutritionally by the plants. It is in the processing of these solids through the degrading and mineralizing properties of bacteria that part of the nutrients released into the system can be assimilated by plants.

The use of an aquaponic cultivation method is one of the most appropriate solutions today as mentioned by the following biologist: "Aquaponics is the solution to the problem of food insecurity, the problem of lack of water for fish farming and the agricultural sector and the solution for arid areas to be exploited with the cultivation of species in this type of Biotechnology" [8].

Giving way to the use of technological solutions as a tool for maximum improvement in the agricultural field through telemetry and the Internet of Things (IoT). Where it is stated: "It is a technology that allows the remote measurement of physical magnitudes and the subsequent sending of the information to an operations center or wherever the user is located; in this way the information is used to monitor and/or control a process in the remote site" [9].

2. Background

The work [10] shows the problems generated in order to provide the necessary energy to operate an aquaponics system, since the current model requires a large amount of energy for the water pumps to make the water flow from the fish to the plants and vice versa. A random feeding method is proposed by means of solar panels that generate energy stored in batteries, the problem that arises is that, due to the high temperatures of Africa and the radiation, the panels heat up, so it is proposed to use the water used by the same system to solve this problem and cool the solar panels, the results obtained when implementing the aquaponic system.

Exposes the importance of aquaponics to solve the problem that is currently presented to generate food sustainably, in order to meet this objective aquaponics requires that the different variables related to water quality are balanced for that reason an IoT solution generates that can be controlled by sensors and actuators these variables[11]. For example, the PH of the water, since by means of a sensor it is possible to measure the amount of acidity of the water and thus determine its PH, this allows to act quickly if there is a variation in this value, because if there is a variation, the life of the fish or plants may be at risk. All this is complemented with a Web monitoring system where the information from the sensors and actuators is collected to generate alerts if there is any change that endangers the water quality.

In [12] we can see the implementation of an IoT system in the aquaponics model and the comparison between a controlled and monitored aquaponics system against a conventional culture, in this case an Arduino Mega was implemented to receive the information from the different sensors implemented (water temperature, room temperature and Ph), additional is in charge of taking corrective measures to maintain the system with all balanced parameters such as water temperature because if it is higher than 25C° activates a cooling system, also this captured information is sent to an Android application through a raspberry Pi that has a camera that also captures the bed of the plants to monitor growth, what was concluded in this work is that a controlled and monitored aquaponic system generate a much more productive crop than a conventional one.

On the other hand, [13] shows how they designed an efficient home aquaponics system using a simple IoT model, they used an Arduino Uno connected to a PH sensor in order to track different scenarios by changing the amount of fish and the amount of plants in this case lettuce, to determine what is the optimal amount of fish and lettuce, for this for 21 weeks they placed compared two scenarios, the first with 30 goldfish and 20 lettuce and the second were 15 goldfish and 30 lettuce, in the first scenario they found that between week 9 to 12 17 fish died, lettuce grew 1. 6cm, the pH value was 6.6, nitrite 0.44ppm and nitrate 30 ppm and finally the fish grew 0.3 cm, on the other hand in the second scenario.

According to an article in Consumer magazine [14], it has been evidenced that there are a number of drawbacks when maintaining an aquaponic system, because one must be aware that a balance must be maintained in everything, specifically variables such as temperature, PH, humidity and others should be taken into account, as they can directly affect the growth of plants and fish life. According to[15], PH is one of the factors that is related to nitrification in aquaponic systems, for nitrification to be generated optimally the PH should be maintained in a range of 6 to 9, or 7.2 to 7.8. As for the temperature, according to an article [16] it is said that the adequate temperature in aquaponic systems for the prosperous growth of plants is 23.8°C (75°F) although it can vary between 21.1- 23.3 °C (70-74°F), it should be maintained this way because higher temperatures could cause a decrease in the growth of plants and vulnerability to pathogens. And from a study conducted by [17] it was obtained that for a correct growth of lettuce in an aquaponic system, a humidity level should be maintained in a range of approximately 55-85 % of Relative Humidity. Maintaining balanced nitrite and nitrate parameters is important for the health of the fish in the aquaponic system.

In the project presented by [18] a design of an aquaponic system monitored by means of the internet of things and artificial intelligence is discussed, they comment that their model has a structure that is divided into four parts or layers: Sensing, communications, services and applications. According to the research in the services layer, it is explained that this part is responsible for the management and regulation of data sent from the part in charge of communication to perform their respective analysis, visualization, storage and security. As for the service layer, this layer provides the visualization service based on web, mobile, and local. Visualization is directly for monitoring, control, prediction, and logistics. Another service is artificial intelligence, which is where data is inserted to provide information to artificial intelligence models for predicting environmental variables and identifying those responsible for contamination, as well as crop prediction. The elaboration of a history of labeled data was necessary. In the authors' opinion the most used techniques in the application of predictive tasks are: Decision trees, neural networks, support vector machines, Bayesian methods, regression method, lazy methods and ensemble methods. They came to the theory that it was possible with images of the aquaponic system to perform artificial vision processes such as predicting the weight of fish or the state of plants by analyzing the images or videos using color histograms, texture, or logical characteristics of the images specifically in which figures and areas could be evidenced.

In the application layer, where information is processed and managed for users through interfaces. And finally the monitoring of the information, by means of sensors that capture the data to be validated and to make its cleaning process, which allows to have validated information for the realization of prediction models, which end up providing valuable data to make the decision making process more accurate.

According to the authors, when the pH prediction is in the lower range (4.6-5.9), they recommend raising the pH by adding a base or increasing the residence time of the water in the plants. When the pH range is in the middle range (6.0-7.1) they argue that the system is working well and it is convenient to maintain it as long as possible, and, finally, when the pH prediction is in the high range (7.2-8.5) they recommend adding an acid or increasing the water flow from the plants to the fish system.

In the research of [19] a data explorer was applied, which is a function for descriptive analysis in an aquaponics system, whose purpose is the visualization of the data and the possibility of making different comparisons between the variables stored in the system, providing all this information through graphs to improve planning in decision making.
According to the work [20] aquaponics management is improved with IoT-based predictive analytics for efficient information utilization, 2019) argue that aquaponic systems require the implementation of a good management system, monitoring, more specifically they talk about some parts in specific, as they are, Automation (AP) which is composed of the control and data acquisition layer (SCADA), the enterprise resource planning (ERP) area and the manufacturing execution system (MES). All of this along with IOT-based predictive analytics and storing all the information in the cloud to help improve the functionality and success of our aquaponics systems. Predictive analytics using cloud-based IOT helps improve the data acquisition layer and feeding the analytics in real time and with historical data already available, all of this information is what is used to be able to perform predictive analytics and decision making. According to the authors, historical data is necessary because it is used for benchmarking and for creating comparative models and decision making. And as for cloud-based IOT, it brings to the ERP layer greater agility, flexibility and predictability of information in real time.

3. Telemetry system development

As part of the research process, a telemetry system was developed, which integrates sensors that allow the monitoring of physical and chemical variables; this system has a storage module that allows obtaining data from the aquaponic crop in order to analyze its behavior over time.

The telemetry system was implemented at the Gimnasio Bilingüe Campestre Marie Curie School (GCBMB), in a greenhouse with two aquaponics systems. As can be seen in figure 1.

The data acquisition module of the telemetry system was divided into two stages of integration for the sensors. In the first stage, sensors were implemented to measure variables such as humidity, temperature, PH and luminosity; in the second stage, level, conductivity and turbidity sensors were integrated. These variables are monitored in the different components of the system.

The PH and temperature sensors (DS18B20) are located in the fish tank, the humidity sensor was integrated in the culture beds, and to monitor the general conditions of the system in the greenhouse, a luminosity and relative humidity sensor was included in the first stage of implementation. Subsequently, an ultrasonic sensor was incorporated to monitor the water level, turbidity and conductivity in the floating beds of the crop for a second stage of data analysis of the aquaponic crop.

Fig. 1. Aquaponic Systems

Figure 2 shows the places where the plants are located with the different sensors for humidity, temperature, PH, turbidity SEN0189 and conductivity DS SEN0244.

Fig. 2. Sensors placed on plant crops.

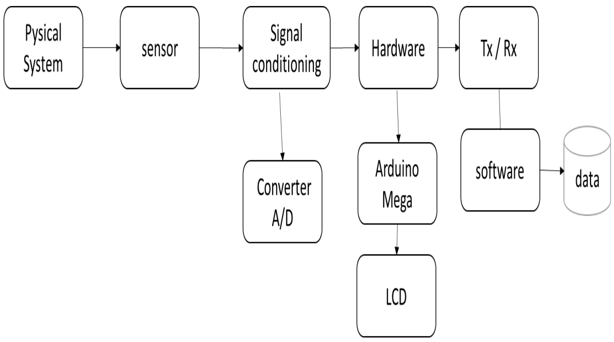

Fig. 3. Block diagram of the system

Figure 3 shows a block diagram of the system, starting from the physical variables that are obtained from the aquaponic assembly, in the next block are the different sensors, analog and digital, requiring a signal conditioning stage by means of software to perform the necessary analog-digital conversion.

Figure 4 shows the Arduino Mega board that was used as data acquisition hardware due to the number of analog and digital inputs it has, allowing the monitoring of the variables simultaneously. It should be noted that in order to visualize in situ the measurements of the sensors, an LCD was incorporated to the assembly for this purpose, later an

Ethernet module is integrated for the transmission of data by ease in the infrastructure of the institution.

The board has a microcontroller that performs the following routine:

- It runs a timer that guarantees to take, process and send data every minute.
- Analogue voltage values are sampled from the pH and water temperature sensors.
- Voltage-to-equivalent conversion calculations are performed on pH and water temperature variables.
- Digital data from the brightness, ambient temperature and relative humidity sensors are processed.
- All measured values are stored in time variables.
- Communication block is built by implementing security token for HTTPS communication.
- Information is sent in an HTTPS request to a cloud server via the internet.

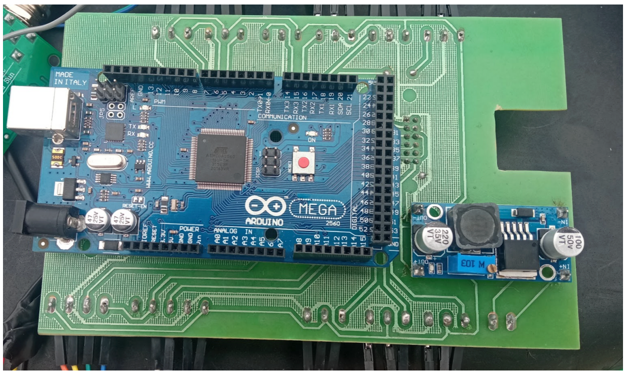

Fig. 4. Data acquisition hardware.

4. Software development

Data is acquired and preprocessed locally before being sent to the cloud processing system. Sending data from a microcontroller to a web server via an API (Application Programming Interface) is a process that allows information to be collected from a device and transmitted to a remote processing system for analysis and storage. For this purpose, a software solution was developed that exposes in public access on the Internet an API that receives the packets sent from the microcontrollers.

A REST API was developed in C# programming language that implements security and scalability measures to ensure that it does not collect data from unauthorized sources and also that it can be used by many microcontrollers at the same time.

The data received in the cloud, from the processing cards are stored in a PostgreSQL database, these data are received by an application built in APS.NET CORE that can be consulted through a graphical interface built in React JS and Next JS.

Two API clients generated in ASP .NET have been developed, the first client will be an application generated in React Hooks where the application can be managed (registered devices, users, variables and alerts) and where the information captured by the processing cards can be observed. The second API client will be responsible for capturing the information from the different sensors located in the aquaponics systems.

It will have a security layer that allows to validate that you can only communicate with the API Rest if you have the respective security token (JWS), in the API REST layer will process all requests from different customers and this layer will access the database where all the information of the users of the application, the devices that capture data, the information captured and the alerts that are configured by users.

5. Web solution architecture

The web architecture of the solution contemplates the use of multiple web clients located in each telemetry system located in each aquaponics system. These web clients must use security implementations based on the use of a security token (JWS - JSON Web Signature) that verifies the security layer. A cloud computing instance was implemented that hosts the developed software in charge of doing the security validations and having the API that receives and validates the data sent by the microcontroller, to be stored in a database in the cloud, as can be seen in Figure 5.

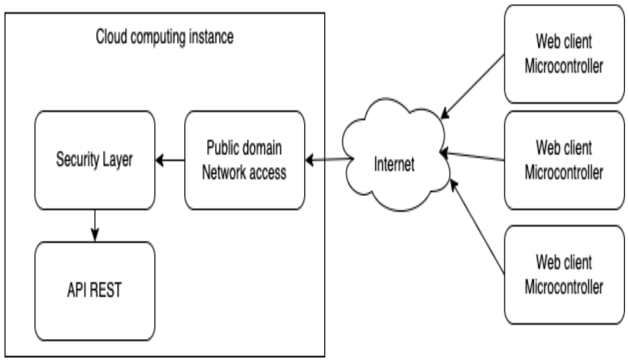

Fig. 5. Model Architecture Project

6. User Interface

A user interface was developed to manage the telemetry systems authorized to use the API and cloud storage. It also allows viewing the historical information of each of the variables measured in each aquaponic system, as shown in Figure 6.

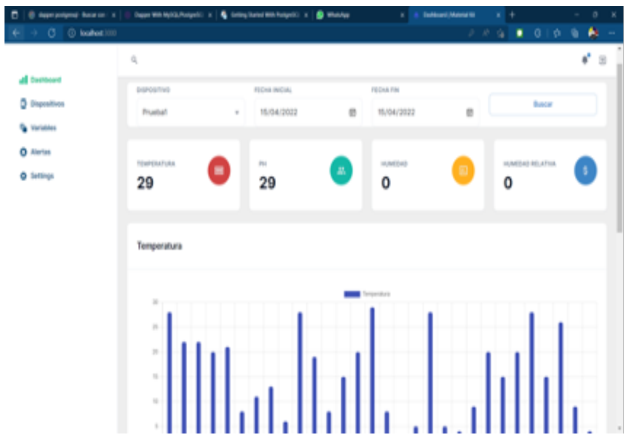

Fig. 6. User Dashboard

Data analysis capabilities were developed, allowing descriptive statistical analysis by means of historical graphs, histograms, and some other descriptive techniques such as boxplot analysis, as can be seen in figure 7.

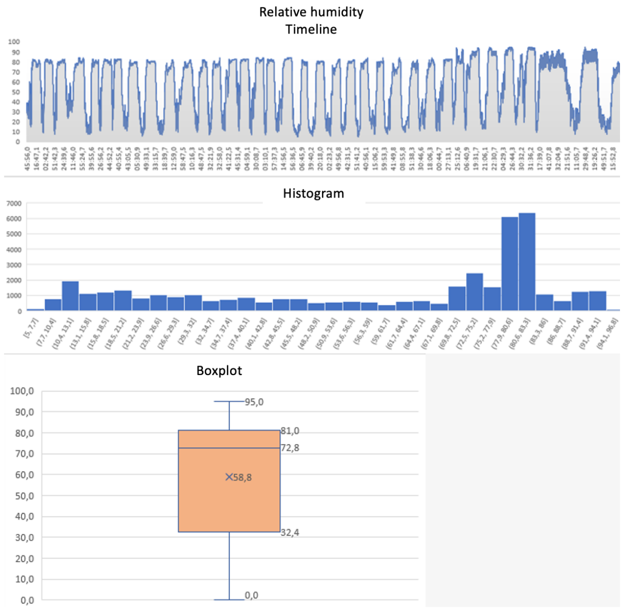

Fig. 7. Data analysis feature of user interface.

7. Results

For the analysis of results, data collection was carried out during 1 month, the amount of data is presented in Table 1.

Table 1. quantity of data collected in 1 month

Variable	Number of data x month
Fish PH	37097
Luminosity	39523
Temperature Plants	34568
Relative Humidity	32912
Plants PH	36011
Environmental temperature	33147

8. Data Analysis

Data captured by the sensors were explored and filtered to obtain meaningful observations. For this, we focused our analysis on a three-month duration between October and December 2022 where we removed nonsensical value and sensor misreads from the dataset. Additionally, we resampled all data in intervals of 15 minutes by averaging every recorded entry of each variable in each interval. The resulting dataset is represented in the form of time series in Figure 10. While pH measurements of the fish and plant tanks showed drastic changes in the three-month span; fish tank and room temperature, luminosity and relative humidity showed clear oscillations in the daily scale. Such trends are highlighted in the top panels of Figure 8 (in red), where we can see such dependencies by the hour of the day.

In order to explore further the relationship and dependencies between our measured variables, we performed a Principal Component Analysis (PCA). We chose to use three components, explaining about 94% of the total data variance. We identified clear factors that describe each component, which we define here as: environmental component (PC1, 47.0%), water acidity component (PC2, 31.1%) and water temperature component (PC3, 15.6%). In Figure 9 the relative contribution of each variable to these components are visualized with a biplot (Figure 9A) and a heatmap (Figure 9B).

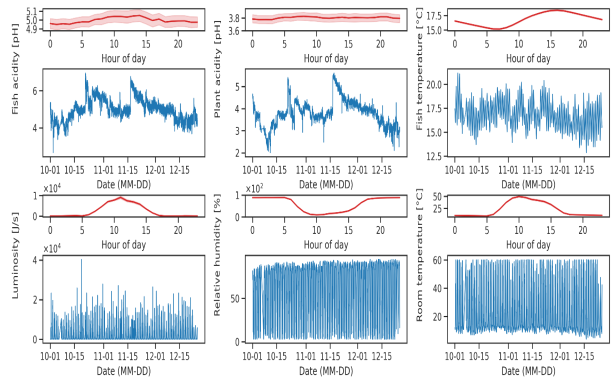

Fig. 8. System 2 acquired data overview. Top panels (in red) data grouped by hour of day (mean and shaded 95% confidence interval). Bottom panels (in blue) all data resampled at 15 minutes intervals.

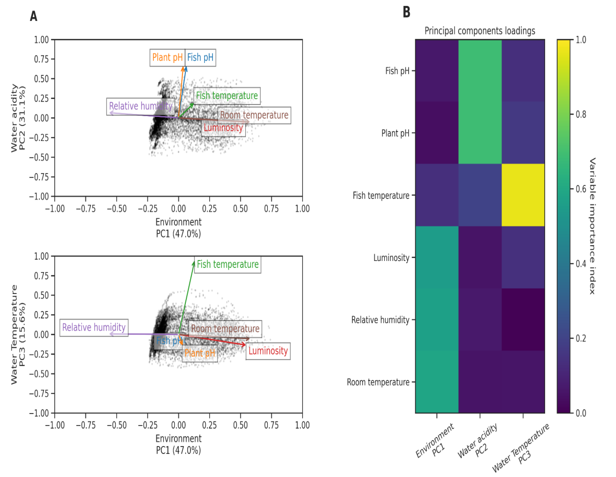

Fig. 9. PCA analysis. A) PCA biplot showing respective components scores and loading of the variables for PC1-PC2 (top) and PC1-PC3 (bottom). B) PCA loadings heatmap to highlight relative importance of the variables in each component.

Finally, we focused on the room temperature variable, thinking that it could have a large impact on the other recorded variables of the aquaponics system. In Figure 10, we show that the recorded room temperature is considerably variable and overall higher during the days (between 8am and 4mp), and much lower and with less variation during the evenings and nights.

Seeing the drastically different behavior of room temperature per hour of the day, we reasoned that we should investigate the relationship between room temperature and the other observed measurements per hour of the day instead of treating it globally. In Figure 11, we showcase a univariate linear regression performed every 4 hours in our system. As the sun heats the system, we could observe strong significant correlation between room temperature and luminosity during the day. Additionally, we could show that room temperature is inversely correlated with relative humidity, where humidity would rise at low temperatures independently of the hour of day, as theory predicts.

Interestingly, we can observe a strong significant correlation between room temperature and fish acidity, plant acidity and fish temperature only at low temperature typically present at night. While during the day, the linear relationship closes to non-significant levels of correlation for these variables.

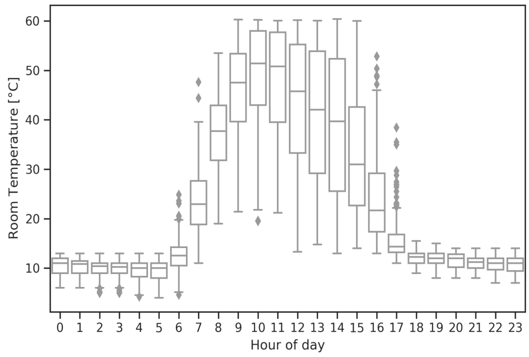

Fig. 10. Room temperature distribution per hour of day.

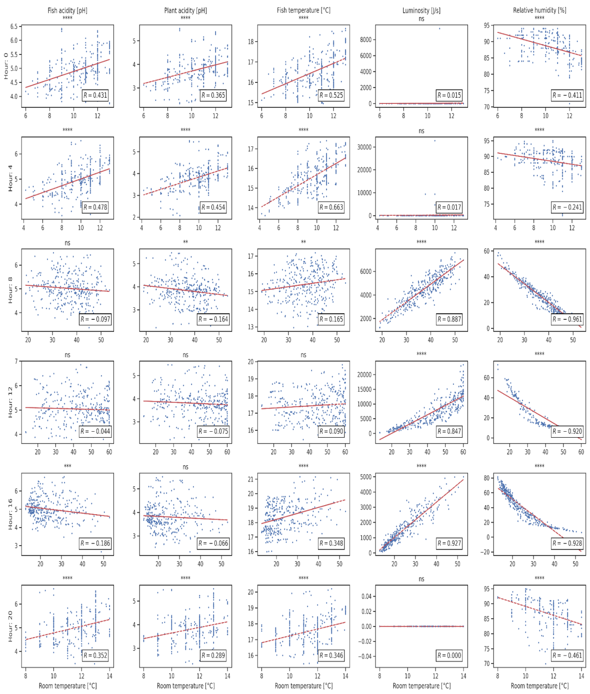

Fig. 11. Room temperature univariate analysis per hour of day. Each column shows a measured variable labeled on the top of the grid and each row shows data from a particular hour of day in an interval of 4 hours labeled on the left of the grid. Pearson correlation coefficient are showed in each plot and the symbolic representation of significance levels of non-zero correlation are present on top of each subplot. See Table 2 for p-value symbols reference.

Table 2. P-value symbol reference.

	Symbol
P-value < 0.0001	****
0.0001 > p-value < 0.001	***
0.001 > p-value < 0.01	**
0.01 > p-value < 0.05	*
p-value > 0.05	ns

All codes for the data treatment, analysis and figure creation are shared on Gitlab

9. Conclusions

The developed aquaponics system is able to acquire, stream, and store large amount of data of many environmental variables at high frequency.

The automatic scripted analysis is suited for the validation of the aquaponics system and allows for gaining insights from the data in short period of time and it can be potentially deployed to run continuously on streamed data.

Exploratory analysis is able to detect errors and outliers in the recorded data. This can guide the development process of the system and help check and maintain the quality of the sensors and telemetric setup.

We show that recorded environmental variable are in line with their physical properties and expected behaviour. This serves as an internal control of our system but also as a good predictive model for future measurements. Particularly we find luminosity and room temperature to increase during the day, while relative humidity would be highest during the nights. Measured fish water temperature oscillates periodically with the time of day with a sinusoidal behaviour being lowest in the early hours of the morning and highest in the middle afternoon.

We show that the overall system can be described at large by three components: one describing the surrounding environment (PC1), one describing the water acidity (PC2) and one concerning the water temperature (PC3). Such components have clear relationship with the physico-chemical ecosystem in which they are measured and they can be good descriptors for larger system in the future.

We show that overall room temperature in the greenhouse has a large variability and can have a strong impact on the other environmental variables. Of particular interest is the fact that tank water pH and temperature are strongly correlated with room temperature only at night (lower temperatures) but seem to be completely regulated during the day (higher temperature), suggesting complex physico-chemical and biological regulation in the system.

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