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Original Article

Design and Implementation of a Hydroponic System Using Monitoring Sensors for Lettuce Crop Data Control

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Abstract - *This paper proposes implementing an automated hydroponic system that uses sensors for nutrient monitoring and control by measuring the electrical conductivity of the substrate. The system includes the control of a water oxygenation pump and pH and conductivity sensors connected to an ESP32 microcontroller. In addition, the monitoring system incorporates LoraWAN communication modules, which allow transmitting sensor data over distances exceeding 8 kilometres, which is ideal for applications in large agricultural environments. This device sends the collected data to a server in the cloud, where it is processed in an analysis layer. As a result, optimal control of seedling growth is achieved, in addition to obtaining a data set of different variables and finally identifying key variables that influence plant development.*

Keywords - *IOT, Precision Farming, NFT System, Hydroponics, ESP32, Sensors, Lora Wan.*

1. Introduction

This research stems from the need to understand the context and assess the acceptance of hydroponic crops in urban areas. In the same way, we can identify the benefits of using these crops and the efficient management of natural resources. With improved pest control, toxic pesticides that harm the environment and consumers' health are avoided. Crops grown using this technique require, on average, much less water. Up to 90 percent of the water used for these crops can be recycled. Another benefit of hydroponics is that it does not require agricultural machinery or much physical effort, thus providing greater cleanliness and food safety from planting to harvest. Thanks to this, we can be sure that the food will be free of agrochemicals or harmful products" [1].

Modernism has allowed the introduction of the most recent advances in electronics, informatics (hardware and software) for the control and execution of activities and new technologies in communications and geographic information, which have made the automation of hydroponic cultivation a reality and an increasingly widespread trend with the consequent economic and management benefits [2]. Sensors can monitor the conditions in which the crop is being grown in real-time: humidity, temperature, or chemical indicators, for example. To detect certain problems and make decisions more appropriate to the situation at a given time. The background mentioned below will allow the implementation of various technologies to control the measurement, monitoring, and control of the physical variables of the nutrient substrate to sustain the ideal conditions of the crop. In the current market, there are devices capable of measuring electrical conductivity, pH, alarms, and control through cell phones [3]. Greenhouse crops allow pest control, but there are problems related to working time, control, and monitoring of nutrient flow and environmental conditions in the greenhouse, which have been tried to be solved with conventional forms of automation. This project seeks to improve a type of NFT (Nutrient Film Technique) hydroponic cultivation of vegetables in greenhouses using real-time control and monitoring of some of its variables such as greenhouse and nutrient solution temperature, adequate control of nutrient flow, monitoring of the electroconductivity of the nutrient substance, pH and the different percentage measurements that make up each nutrient in the solution [4]. In agriculture, the Internet of Things has been utilised to control the environment of cultivated plants. Due to unexpected climate change caused by humans or nature, plants are affected and have low yields. As a result, maintaining an optimal climate by controlling humidity and temperature is essential for plant growth in a hydroponics system. The Internet of Things is more applied in intelligent farming. Hydroponics has enabled the growth rate of hydroponic cultivation using the Internet of Things-controlled environment to be up to 50% higher than that of soil cultivation [5]. Consequently, the IoT system has contributed to the optimal development of hydroponics. However, precision is required in certain parameters, such as water pH and nutrient TDS, because this can influence the growth of the crop and prevent it from reaching optimal development. Likewise, a monitoring system is proposed for lettuce crops in a hydroponic system type NFT to optimise the calculation of nutrients in the crop, which is developed by collecting data through temperature, humidity, pH, and TDS sensors. These data are sent to an IoT platform called ThingSpeak for monitoring.

1.1. State of Art

The work focuses on the automation of a hydroponic NFT (Nutrient Film Technique) greenhouse cultivation system, which is monitored through a web platform. This system is used for growing lettuce, and the project seeks to optimise the control of key variables such as temperature, pH, electroconductivity, and nutrient flow. By implementing sensors and controllers, efficiency is improved, and human intervention is minimised, promoting a more sustainable and efficient crop in terms of resource use and pest management [6]. The project aims to optimise the control of key variables such as temperature, pH, electroconductivity, and nutrient flow.

The paper proposes an intelligent agricultural system based on an IoT platform, which collects data related to fertilisation, soil, environment, and irrigation to perform data correlation and filtering. It highlights the capability of crop forecasting and prediction to improve agriculture. The proposed model integrates with IoT sensors and supports data storage in the cloud, ensuring stable connectivity between devices. The main objective is to propose an IoT-based smart farming system that collects essential data to improve agricultural management, including crop forecasting and optimisation. It seeks to integrate sensors and technology to provide a complete and efficient solution to the problems of modern agriculture [7].

The proposed Smart Agriculture system monitors and controls key agricultural parameters such as temperature, humidity, movement, and water level in the field. Through an Arduino Uno controller and various sensors, plant irrigation is automated according to the detected needs, optimising crop management and reducing manual intervention. The IoT-based Smart Agriculture system aims to improve agricultural productivity through automated monitoring and control of parameters such as temperature, humidity, movement, and water level in the field. Using technologies such as sensors and controllers, it seeks to optimise plant irrigation and maximise crop yields [8].

Based on the Internet of Things (IoT) technology and deep learning algorithm, a greenhouse intelligent agriculture management system was established to analyse the application value of the intelligent agriculture remote monitoring management system in the greenhouse planting industry. Based on the analysis of greenhouse planting demand and environmental factors, the intelligent agriculture monitoring system is established based on the IoT, and the greenhouse system controller is designed based on the adaptive proportion integration differentiation (PID) algorithm [9].

The article provides a detailed study on designing and implementing an automated agricultural control system using Internet of Things (IoT) technologies and wireless sensors. The system components, which include temperature, humidity, and CO_2 sensors, as well as a central controller and a coordinator to manage the automation, are described. Results obtained from monitoring environmental variables such as temperature, humidity, and CO_2 are detailed, showing how the automation responds to this data to control ventilation and cooling systems. System challenges and limitations, such as loss of sensor accuracy and connectivity issues, are also discussed. In addition, a list of references is provided for those who wish to explore the topic of smart farming and IoT technologies further [10].

In summary, several hydroponic systems were analysed, identifying the NFT (Nutrient Film Technique) system as the most optimal, especially for its efficiency in the use of space. In the monitoring systems used in the related works, key variables for the research were identified, such as temperature, humidity, pH, and Total Dissolved Solids (TDS). In summary, monitoring systems in hydroponics prove to be a viable and efficient tool to optimise the use of resources; however, they also present limitations, such as the possible loss of precision in the sensors and connectivity problems.

2. Theoretical Framework

2.1. Precision Agriculture

Precision Agriculture" (PA) is nothing more and nothing less than the consequence of the irruption of IoT in agriculture, i.e., the manifestation of the digital era in agricultural production. Once again, farmers have to become familiar with the tools of the time: keyboards, screens, selection of menu options, etc., as well as the technologies available to achieve agricultural production themtoo to feed a growing world population of seven billion people, with the restrictions imposed by food safety, the conservation of natural resources and the laws of the market economy [11]. In addition, Precision Agriculture allows for more efficient and localised management of agricultural inputs, such as water, fertilisers, and pesticides, reducing costs and minimising environmental impact through sensors, GPS, and data analysis platforms.

2.2. Hydroponic Cultivation

Hydroponics is a set of techniques that allows the cultivation of plants in a soil-free environment, whose growth is possible thanks to the supply of nutrients through water, and a nutrient solution provides the essential mineral elements.

They are ideal for research with plants in controlled or semi-controlled environments. In this system, nutrient uptake is important for each plant's development. When grown in soil, plants use considerable energy to find nutrients through their roots [12]. The diet in hydroponic production is very optimal and based on the plant's needs, which allows these products to have a better and healthier quality than their counterparts in soil cultivation. Because of the precise regulation of watering and feeding the plant, this method is superior to the traditional method [13].

2.3. Advantages and Disadvantages of Hydroponic Cultivation

Although hydroponics has many advantages compared to traditional agriculture, it also has some disadvantages that should be known before starting the research. The described technique offers multiple advantages, such as eliminating the need for soil as a growing medium and allowing an environment free of bacteria, fungi, and parasites. This contributes to higher crop quality and faster production. In addition, it optimises and saves resources such as water and fertilisers, achieving higher production per unit area without requiring agricultural machinery. Its low environmental impact and the use of automated systems make it an efficient and sustainable alternative [14]. This system has some disadvantages, such as an investment cost that can be medium to high, which could be an initial barrier. In addition, bas knowledge of plant physiology and nutrition is required since a lack of knowledge about the appropriate system for a specific crop or proper nutrient management can significantly impact crop quality and yield [15].

2.4. NFT System

The NFT (Nutrient Film Technique) hydroponic system is based on the continuous recirculation of a nutrient solution through a series of channels formed by PVC pipes. This solution is directed towards a main container with a submersible pump, which drives the water flow at programmed intervals, ensuring adequate oxygenation. Along the way, a thin film of nutrient solution comes into contact with the plant roots, which hang from baskets arranged in the channels, thus allowing efficient nutrient absorption [16].

In addition, the system is composed of distribution tubes, baskets with sponges to support each plant, a storage tank, the nutrient solution, and an electric pump that guarantees the proper functioning of the circuit. The channel pipe is slightly tilted so the nutrient solution will flow with gravitational force. This system works very well because the plant roots absorb more oxygen from the air than from the nutrient solution [17]. As a result, the root tips are in contact with the nutrient liquid, and the plants have access to more oxygen, favouring faster growth. The nutrient solution is circulated and has nutritional content that considers the needs of the plants. The root system can grow on a mixture of nutrients. Moreover, several factors must be considered, such as when excessive water will occur and factors decreasing the amount of oxygen. The nutrient content of the NFT method is specially designed, with a maximum solution height of 3 mm, so that water, nutrients, and oxygen needs can be met [18]. The TDS sensor detects the level of nutrients in the liquid, and the pH sensor provides data on the pH of the liquid to ensure that plant growth is not affected.

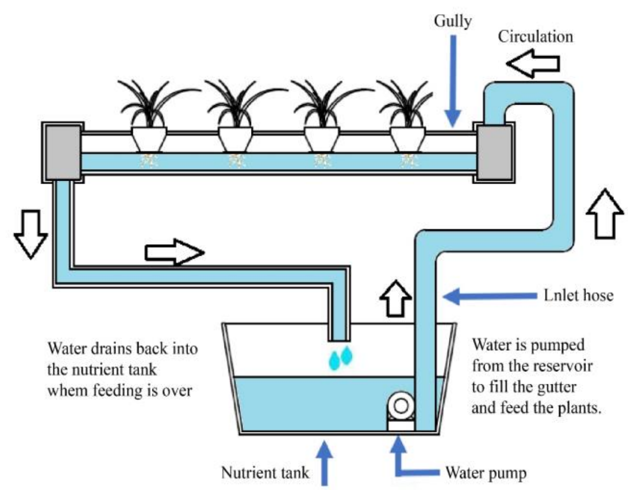

Fig. 1 Hydroponic NFT schematic diagram

2.5. Implementation of Hydroponic Growing Systems

The following is a general explanation of how to build a hydroponic growing system:

Channel Design: The NFT system consists of sloped channels or pipes where the plants or vegetables will be placed. These channels should be made of non-transparent material to prevent algae growth and have a slope of approximately 1-2% to allow for a constant flow of the nutrient solution.

Nutrient reservoir: A tank or reservoir is needed to hold the nutrient solution. This reservoir should be large enough to maintain a constant supply of nutrients and water for the culture.

Pump and Piping: A submersible pump is used to pump the nutrient solution from the reservoir to the top of the canals. Piping and fittings must be installed to allow the solution to flow along the channels.

Plant and substrate: Plants are placed in small containers or baskets inserted into the holes in the channels. An inert substrate, such as rock wool or perlite, supports the plants and provides a medium for the roots to grow and absorb nutrients.

Nutrient solution flow: The solution is pumped from the reservoir to the top of the channels and flows in thin film along them. The roots of the plants are exposed to this film of nutrient solution, absorbing the necessary nutrients.

Recirculation and drainage: The nutrient solution flowing through the channels is collected at the bottom and returned to the reservoir for recirculation. A proper drainage system must be in place to prevent water accumulation and ensure that the NFT system functions properly.

Monitoring and adjustment: It is essential to regularly monitor pH levels, EC (electrical conductivity), and temperature to ensure proper nutrient balance. Periodic adjustments may be required to maintain optimal plant growth conditions.

2.6. Hydroponic Crop Monitoring System

A monitoring system for hydroponic crops is a tool that facilitates the observation and regulation of the main factors that affect the production of these crops. These systems are usually inexpensive and use Internet of Things (IoT) technologies for their implementation in hydroponics. Such systems can manage the water flow in the crop and monitor aspects such as pH, temperature, humidity, and water reservoir level, providing the data in real-time through a web platform [19]. In addition, these systems contribute to data-driven decision-making, enabling accurate real-time adjustments that improve crop efficiency, reduce resource wastage, and optimise plant growth.

2.7. Measuring Variables of Hydroponic NFT Crops

Temperature: Temperature is an important factor to consider in hydroponic cultivation, affecting plant growth and development. The ideal temperature range for most hydroponic crops is between 18°C and 25°C during the day and between 15°C and 20°C during the night [20]. In addition, temperature influences the rate of photosynthesis and nutrient uptake, so maintaining proper control is crucial to optimise production and avoid plant heat stress.

Humidity: Humidity is a very important factor in hydroponic cultivation, as it affects the absorption of water and nutrients by plant roots and the development of pathogens such as fungi and bacteria. The optimum relative humidity for a hydroponic crop can vary depending on the growth stage of the plant and the type of plant grown, but it is generally recommended to maintain it between 50% and 70% [21]. It is important to note that very low humidity levels can dehydrate plants, while too high levels can promote the proliferation of fungal diseases, so constant monitoring is essential to maintain the proper balance.

PH: Thanks to the pH, it is possible to know if the state of a nutrient solution circulating through the crops is too acidic or base, affecting plant roots to absorb nutrients efficiently. These oscillate between 5.5 and 6.5 acidity, which must be monitored continuously to avoid crop losses [22]. A pH outside this range can prevent the absorption of essential nutrients, which would negatively affect plant growth, so precise control is essential to ensure adequate nutrition.

Electrical Conductivity: Excessively high levels of nutrients induce osmotic stress, ion toxicity and nutrient imbalance, while excessively low values are accompanied mainly by nutrient deficiencies and decreasing plant growth. In soilless culture, the total salt concentration of a nutrient solution is the most important characteristic. Conductivity Factor (CF) is a measure of the electrical conductivity of a nutrient solution read in mS/cm (mill semen per centimetre) and sometimes given as µs/cm, which can be multiplied by 1,000 to convert to mS/cm [23]. Electrical conductivity also indicates the concentration of nutrients available to plants, allowing nutrient solutions to be adjusted more efficiently and ensuring that plants receive the correct amount of essential elements.

2.8. Nutritional Solutions

The nutrient solution is composed of water enriched with oxygen and essential nutrients dissolved in ionic form. Its components also include certain organic compounds, such as iron chelates. For the nutrients to be effective, the solution must be completely homogeneous, i.e., all ions must be fully dissolved. If any of these nutrients precipitate and are no longer available in ionic form, it can lead to a deficiency in the crop [24]. In addition, this type of alteration also affects the ionic balance of the solution. In systems such as aquaculture, the nutritional requirements of plants are covered by this nutrient solution, and the amount of nutrients needed varies according to the plant species, variety, stage of development, and environmental conditions.

The nutrient solutions correspond to the mixture of nutritive elements, which are all the essential elements that are supplied with salts dissolved in water. The relative proportions of ions are introduced with the necessary formulation of macronutrients known as nutrient solution A, which is required in greater proportion, and micronutrients known as nutrient solution B, which are required in smaller amounts but very important for crop development [25].

Tabla 1. Macronutrientes y micronutrientes

Solution A	Nutrient solution B
Monoammonium phosphate Potassium nitrate Calcium nitrate	Boric acid Zinc sulfate Manganese sulfate Copper sulphate Magnesium sulphate Ammonium molybdate Iron chelate

2.9. Materials

2.9.1. ESP32

It is a programmable microcontroller developed by Express, which allows Wi-Fi connectivity for an economical price. One of its main features is that it can be used independently or as a transceiver 24 with other microcontrollers through the serial port through the TX and RX terminals. It has 1 pin analogue and 13 digital inputs. For application development, code can be written in the Lua language using the Arduino framework. In addition, Arduino allows the use of the libraries developed for Arduino and works within its integrated development environment (IDE) [26]. Additionally, the ESP32 is widely used in IoT projects due to its low power consumption and ability to handle multiple tasks simultaneously, making it ideal for real-time monitoring and control applications.

2.9.2. Sensor FS400-SHT31

It is a device designed to measure temperature and humidity in various indoor and outdoor environments. It is part of the SHT31 series, recognised for producing compact sensors that offer high accuracy and low power consumption [27]. In addition, these sensors are ideal for applications that require continuous monitoring of environmental conditions, such as in intelligent climate control systems and crop monitoring, where accurate temperature and humidity measurement is crucial for optimal control of environments.

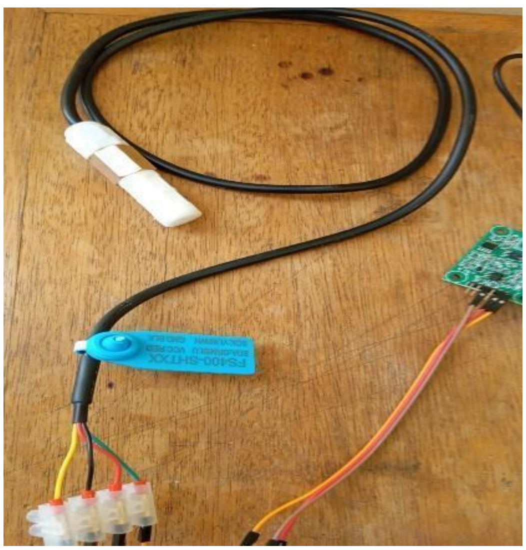

Fig. 2 Temperature and humidity sensor FS400-SHT30

Table 1 describes the characteristics of the temperature and humidity sensor used for the hydroponics system.

Table 1. Características del sensor de temperatura y humedad

Characteristics	
Description	**Worth**
Working current	<10mA
Temperature range	-20ºC – 100ºC
Humidity Range	0-100% RH
Working conditions	-40º C – 120ºC
Housing material	Stainless steel and plastic
Interface	I2C
Cable length	150 cm

2.9.3. PH Sensor

For this type of cultivation that was implemented, it is unnecessary to have a sensor that can be in contact with the nutrient solution indefinitely because PH is a slow variable. A PH V2 sensor was implemented [28] to measure this variable. This type of sensor is suitable for applications where periodic pH monitoring is required since it offers a reliable and accurate measurement without needing constant intervention, optimising resources and simplifying maintenance.

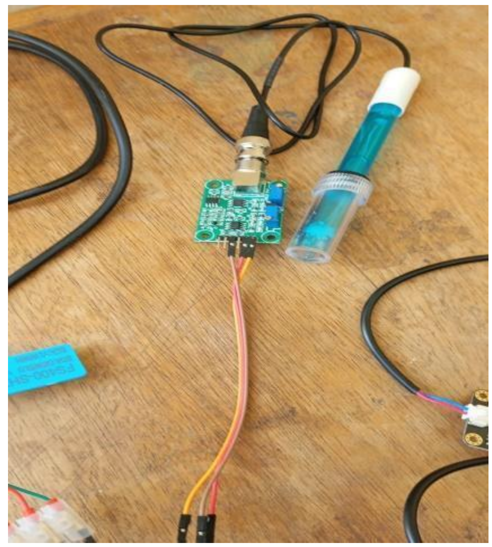

Fig. 3 Sensor de PH V2

Table 2 details the technical specifications of the PH sensor implemented in the hydroponic system. These data allow a better understanding of its functionality.

Table 2. Características del sensor PH

Characteristics	
Descripción	**Valor**
Input Voltage	5Vdc
Measuring range	0 – 14PH
Measurement temperature	0 – 60ºC
Precision	±0.1pH (25ºC)
Response time	≤ 1 min
pH sensor connector	BNC
Interface	pH2.0 (parche de 3 pies)
Gain adjustment potentiometer	Yeah
Module size	43mm x 32mm

2.9.4. Analog TDS Sensor

The TDS sensor uses the electrical conductivity method, where two probes are immersed in a liquid or solution, and then a signal processing circuit will produce an output that shows the conductivity of the solution. This sensor has 3 pins: DATA, VCC and GND. The DATA pin is connected to the Arduino analogue pin (A0), VCC is connected to the regulator output pin, and GND is connected to the regulator ground pin

[29]. In addition, EC monitoring allows for evaluating the concentration of nutrients available to plants, helping to prevent deficiencies or excesses that may negatively affect their development and yield.

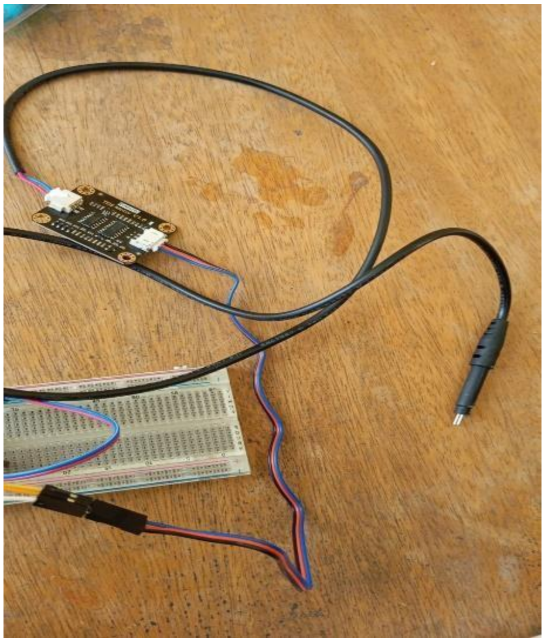

Fig. 4 Sensor gravity TDS meter V1.0

Table 3 presents the specifications of the analogue TDS sensor used in the hydroponic system, highlighting its importance in accurately monitoring and controlling environmental conditions.

Table 3. Características del sensor Analógico TDS

Characteristics	
Description	**Worth**
Input voltage	3.3 - 5.5V
Output voltage	0 -2,3 V
Working current	3 - 6mA
TDS measurement range	0 - 1000 ppm
TDS measurement accuracy	± 10% F.S. (25°C)
Module size	42 * 32 mm
Connection interface	XH2.54-2P

3. Implementation Model

The model is based on a closed-loop control system that, by monitoring variables, determines when it is necessary to activate the nutrient flow system. This is crucial because the roots must remain constantly submerged. However, due to the slope of the pipes, nutrients tend to drop, making it necessary to recirculate them throughout the system. The nutrient level control in the piping was done by keeping the outlet hoses above the desired level. The general scheme of the system is shown in Figure 5.

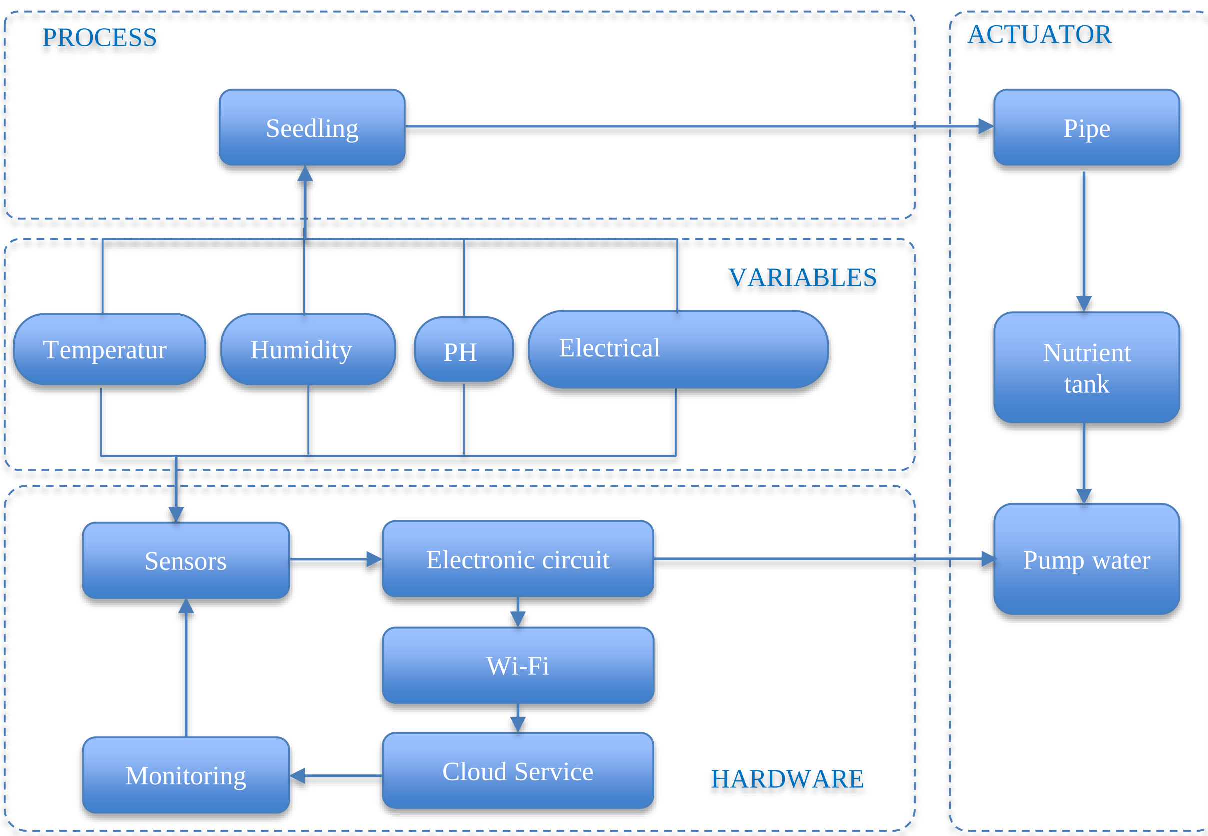

Fig. 5 Block diagram of the hydroponic system

3.1. Design of the Prototype Structure

The design of the prototype structure for a hydroponic system for lettuce cultivation must be conceived with a functional, efficient and adaptable approach to the specific needs of the environment and the crop. Incorporating pH, Electroconductivity (EC), temperature, and humidity sensors is essential to ensure accurate and continuous monitoring of key variables affecting seedling development.

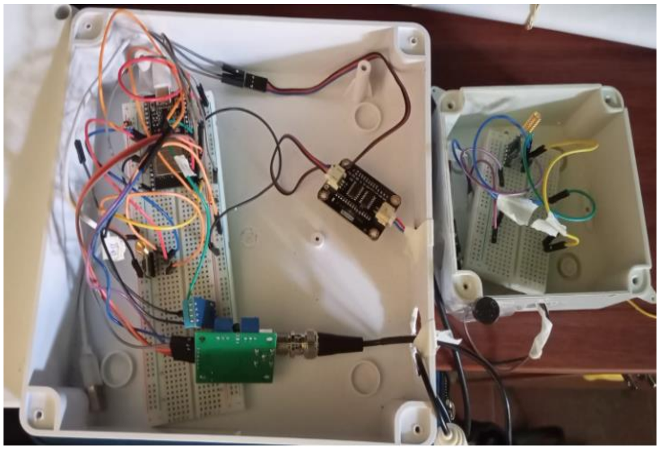

Fig. 6 Prototype with sensors

3.2. Hydroponic Support Structure

Figure 7 shows the proposed design for the structure of the hydroponic system. This structure is made of wood, the channels through which the nutrient solution will flow are made of PVC pipes in 1-meter sections distributed in four levels with a slope of 2% so that the water does not accumulate in the corners, the lettuces are located on each channel and are separated from each other by 20 centimetres; A tank was used to collect the nutritive solution that falls from the canals and then return the solution through 1-inch tubes, which is in charge of storing the solution for irrigation. The different types of sensors are located on the structure; the temperature and relative humidity sensors are next to the main box, and the pH, solution temperature, and electroconductivity sensors are in the T collector tank. This structure supports the culture bed, the microcontroller, the sensors, and all the physical elements used to control the proposed hydroponic process.

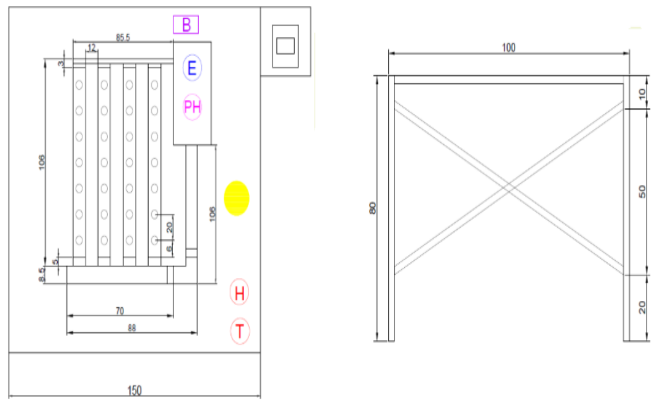

Fig. 7 Structure diagram

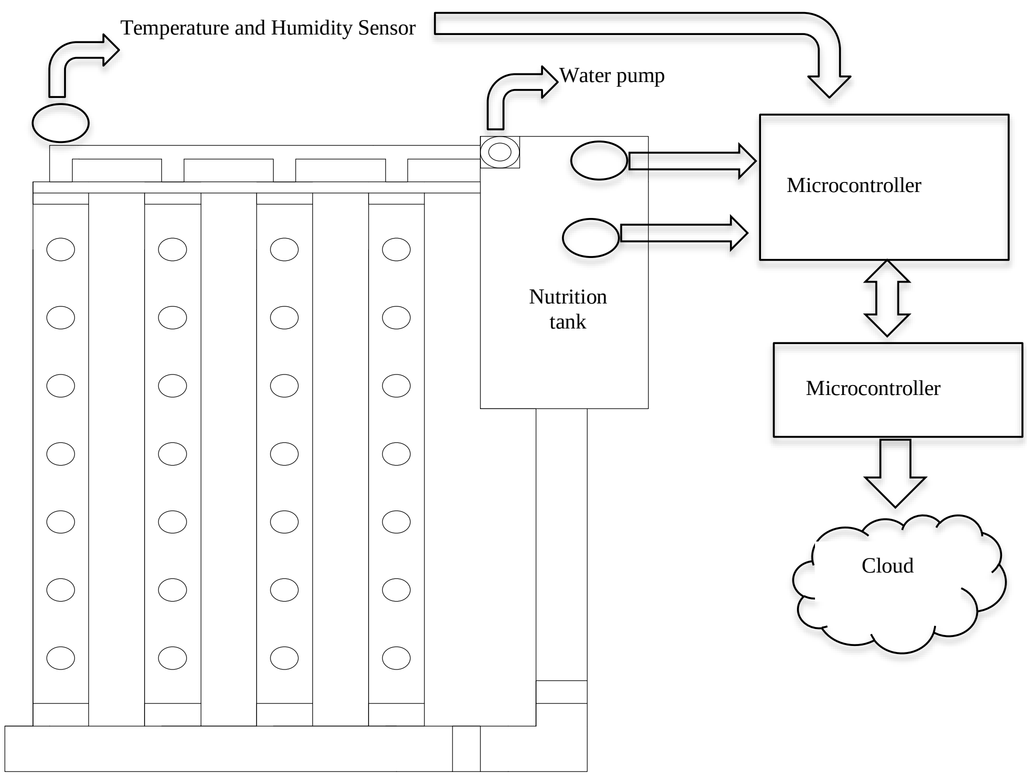

Fig. 8 Schematic of a hydroponic system with integrated sensors and IoT communication

The following is a basic description of the construction of a hydroponic growing system:

Channel Design: The NFT system consists of sloped channels or pipes where the plants will be placed. These channels should be made of non-transparent material to prevent algae growth and have a slope of approximately 1-2% to allow constant flow of the nutrient solution.

Nutrient reservoir: A tank or reservoir is needed to hold the nutrient solution. This reservoir should be large enough to maintain a constant supply of nutrients and water for the NFT system.

Pump and Piping: A submersible pump is used to pump the nutrient solution from the reservoir to the top of the canals. Piping and fittings must be installed to allow the solution to flow along the channels.

Plant and substrate: Plants are placed in small containers or baskets inserted into the holes in the channels. An inert substrate, such as rock wool or perlite, supports the plants and provides a medium for the roots to grow and absorb nutrients.

Nutrient solution flow: The solution is pumped from the reservoir to the top of the channels and flows in thin film along them. Plant roots are exposed to this film of nutrient solution, absorbing the necessary nutrients.

Recirculation and drainage: The nutrient solution flowing through the channels is collected at the bottom and returned to the reservoir for recirculation. A proper drainage system must be in place to prevent water accumulation and ensure that the NFT system functions properly.

Monitoring and adjustment: It is essential to regularly monitor pH levels, Electrical Conductivity (EC), and nutrient solution temperature to ensure proper nutrient balance. Periodic adjustments may be required to maintain optimum plant growth conditions.

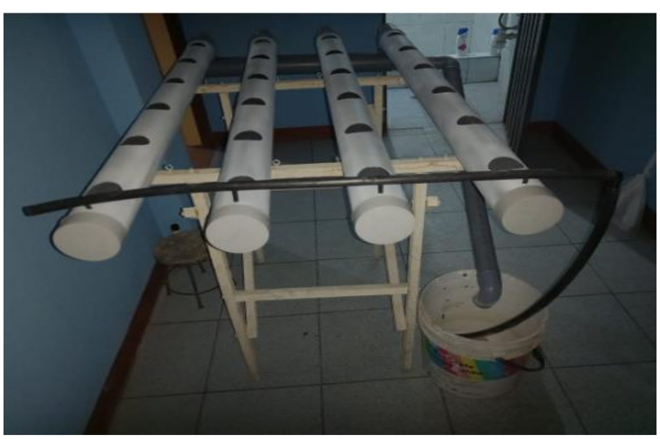

Fig. 9 Hydroponic structure for lettuce cultivation in the NFT system

4. Methodology

In developing the integrated monitoring and automated management system in a hydroponic environment using IoT technologies, a structured approach involving several stages was followed. Initially, extensive research was conducted to identify and select the most suitable components for the system, including pH, electroconductivity, temperature, and humidity sensors, in addition to a microcontroller, a LoRaWAN communication module, and a central server for storage.

Once the components for the hydroponic system were selected, the hardware was assembled, ensuring the proper connections between the pH, electroconductivity, temperature, humidity sensors, the LoRaWAN module, and the microcontroller. Subsequently, the software required to operate the system was developed, which included programming the ESP32 microcontroller, configuring an MQTT server, and designing a user interface to monitor the crop in real time. After completing this stage, extensive testing was conducted to validate system performance under different conditions and scenarios. Factors such as sensor accuracy, wireless communication stability, and efficiency in managing the hydroponic system were evaluated.

Finally, the system was tested in a real environment in Arequipa, Peru, in a 4x4 m2 enclosed area where it was integrated with hydroponic growing techniques to ensure its functionality. This included research and application of appropriate hydroponic methods, installation of the system in a practical environment, and gathering feedback on its performance. This approach allowed validation of the feasibility and effectiveness of the system in real agricultural applications, optimising hydroponic cultivation in specific local conditions.

To evaluate the effectiveness, performance, and feasibility of the automated irrigation and monitoring system, a pilot test was implemented in a hydroponic Nutrient Film Technique (NFT) system in a controlled environment representative of real conditions in the Arequipa region of Peru. This region, known for its diverse climate and importance in agricultural production, provided an ideal scenario to validate the system in a practical and demanding context.

The implementation was carried out during a full growing season, which allowed for analysing the system's behavior at all stages of the vegetative cycle. During this period, detailed real-time data was collected on key parameters such as pH, Electrical Conductivity (EC), nutrient solution temperature, water flow, and general environmental conditions. These data not only helped monitor system performance but also provided valuable information for optimising farming practices.

4.1. NFT System Development

Implementing IoT technologies in agricultural systems, such as the design of an automated irrigation and monitoring system for crops, has been shown to improve efficiency and sustainability in agriculture. In this case, a hydroponic Nutrient Film Technique (NFT) system was developed with four main branches corresponding to four sensor nodes and was designed specifically for hydroponic cultivation. This system uses the NFT technique to guarantee a continuous supply of nutrients and water, promoting healthy root growth and ensuring optimal product quality. Key parameters such as temperature, humidity, and pH were programmed and adapted to the specific needs of the lettuce, considering its ideal temperature range between 15 and 25 degrees Celsius, relative humidity of 60 to 80%, and an optimum pH between 5.5 and 6.5.

Fig. 10 Hydroponic structure in operation in NFT system

4.2. System Architecture

The system designed for the management of a hydroponic crop Nutrient Film Technique (NFT) relies on an Internet of Things (IoT) architecture, integrating various hardware and software components to monitor and control the supply of water and nutrients in an automated way. This approach ensures efficient and accurate management, adapted to the needs of the crop.

The system comprises two main elements: the sensor nodes strategically distributed to measure critical parameters such as pH, Electrical Conductivity (EC), dissolved oxygen level, temperature, and nutrient solution flow. This data ensures an optimal environment for plant growth.

And a web-based user interface designed to provide an intuitive and accessible experience. It allows growers to visualise data in real time, make customised system configurations, and receive alerts on anomalies or specific requirements, even remotely.

This technology integration improves sustainability by reducing water and nutrient consumption and maximises crop yield by providing optimal conditions throughout the growing cycle.

Remote monitoring capabilities and advanced automation make the system ideal for high-precision hydroponic crops.

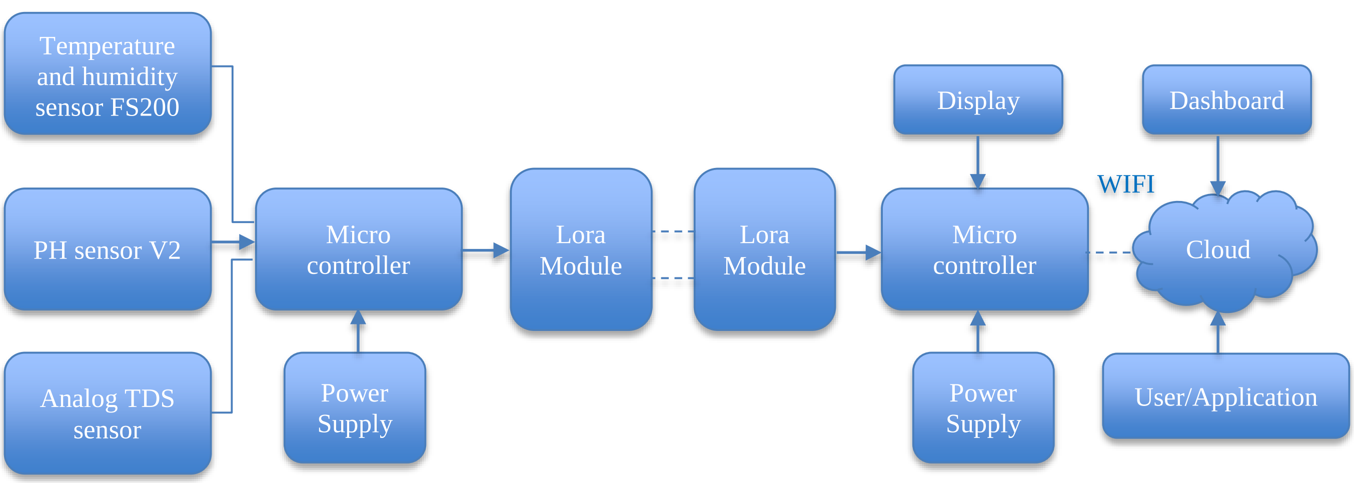

Fig. 11 Block diagram of an intelligent monitoring system

4.3. Nodos Sensors

The system's sensor nodes are designed with an advanced architecture integrating ESP32 microcontrollers, which function as the system's core, enabling efficient data acquisition, processing, and transmission. These microcontrollers stand out for their high processing capacity, flexibility to integrate with various sensors, and ability to manage wireless connections through low-power consumption protocols, making them ideal for agricultural applications requiring constant monitoring. LoRaWAN modules ensure reliable communication between the sensor and central control nodes. This wireless technology is particularly suitable for agricultural environments due to its ability to transmit data over long distances, even in areas with obstacles or without traditional network coverage. In addition, its low power consumption ensures prolonged operation of sensor nodes, reducing the need for maintenance and battery replacement, thus improving the operational sustainability of the system.

4.4. Flow Diagram

The user initiates the process by requesting data in real time. The system checks the availability of the information on the cloud server and responds by displaying the data or issuing an error alert if it is not accessible. Sensors then collect information on essential parameters such as pH, electrical conductivity, temperature, and humidity, which are processed by the ESP32 microcontroller to determine whether crop conditions are optimal. In case of deviations, the system adjusts the nutrient flow by activating the corresponding pump.

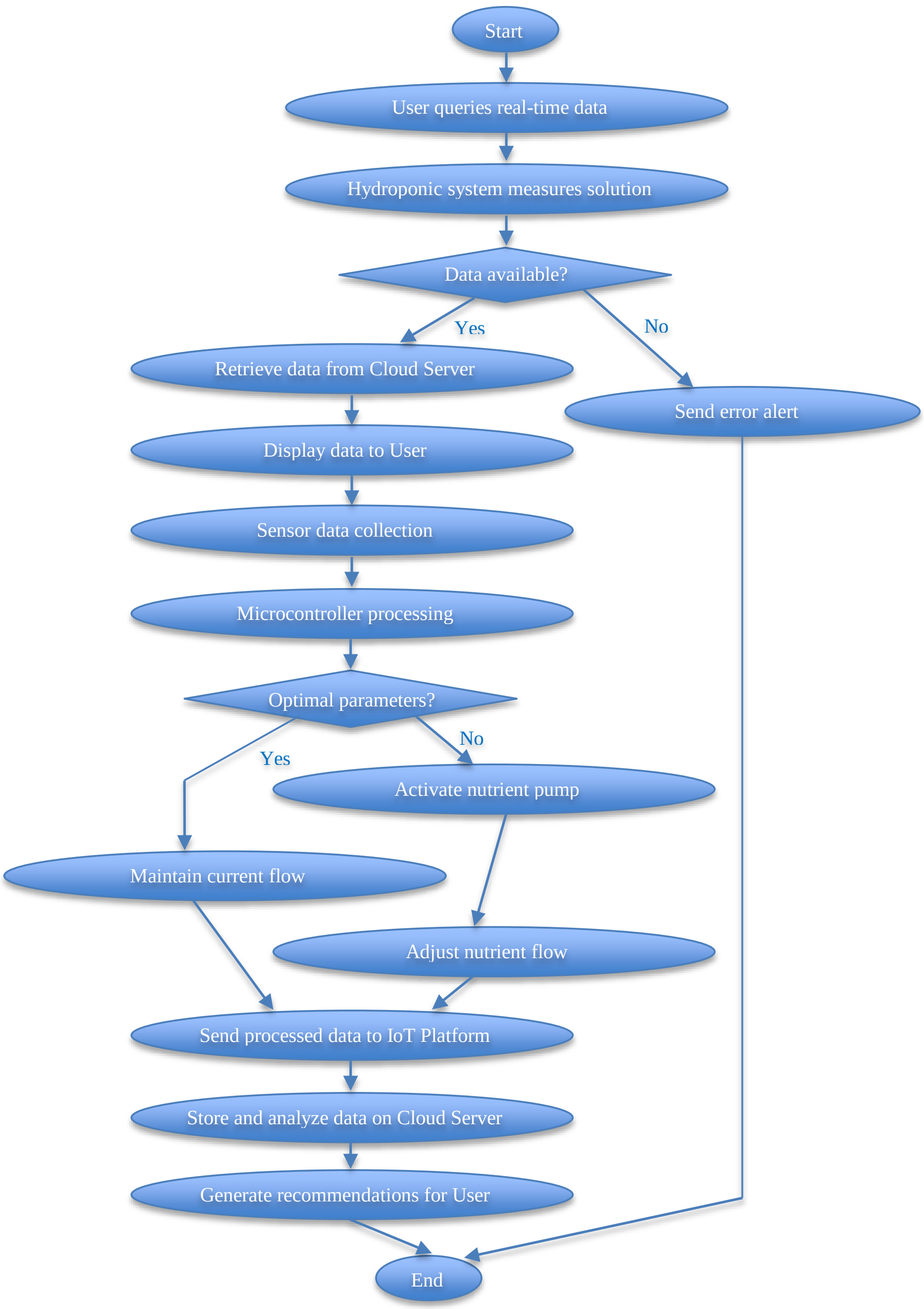

Fig. 12 Hydroponic system flow diagram

Subsequently, the processed data is transmitted to an IoT platform for storage and analysis in the cloud, where personalised recommendations are generated for the user. This approach enables the automation of nutrient control and optimises resources, ensuring a suitable environment for crop development. The combination of sensors, real-time processing, and IoT-based analytics ensures the sustainability and efficiency of the system.

4.5. User Interface

The system is based on an ESP32 microcontroller, which acts as the main server for the web interface, providing a robust and efficient solution for managing the automated irrigation and monitoring system. The ESP32 not only allows real-time data processing and transmission but also supports the wireless connectivity required to access the web interface from any device, which significantly improves the usability and accessibility of the system. The web interface is implemented using ThingSpeak, an IoT platform recognised for providing an intuitive visual representation of data. This tool allows users to interact with the system easily, visualise critical parameters such as pH, TDS, temperature, and nutrient flow, and perform custom settings remotely. ThingSpeak also simplifies the interpretation of trends and patterns with its ability to graph historical and real-time data, helping growers make informed data-driven decisions.

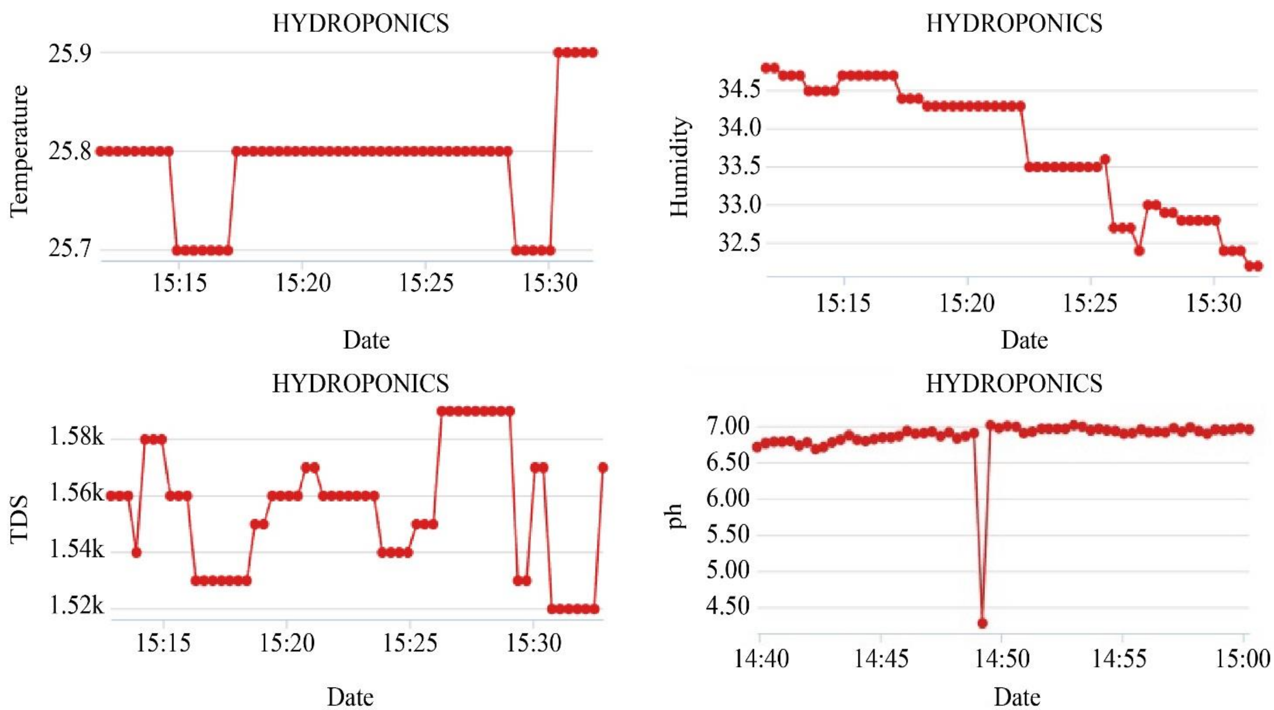

Fig. 13 Temperature, humidity, pH and TDS monitoring in a hydroponic system

In addition, ThingSpeak acts as a database for the storage and management of the data collected by the sensors.

This approach enables detailed analysis of system parameters over time, facilitating the identification of potential problems, irrigation optimisation, and improved crop performance.

The integration of this functionality ensures that data is used in real time and archived for further analysis.

5. Result

This section will present the results obtained, organised in three parts: the first corresponds to the accuracy of the sensors compared to manual measurements made by conventional measuring devices; the second part analyses the impact of the proposed system compared to common techniques used in hydroponics; and the third part evaluates the development of the plants when using the proposed monitoring system in contrast to a hydroponic system without monitoring.

5.1. Results Sensors vs. Manual Sensors in NFT Hydroponic System

The evaluation and comparison of the sensors of the system as manual sensors have been achieved by monitoring the values in the path of plant development by collecting the measurements manually until the harvest of lettuce also managed to obtain the margin of error that is between 0.01 to 0.04 accuracy of each sensor in the system as shown in Figure 15.

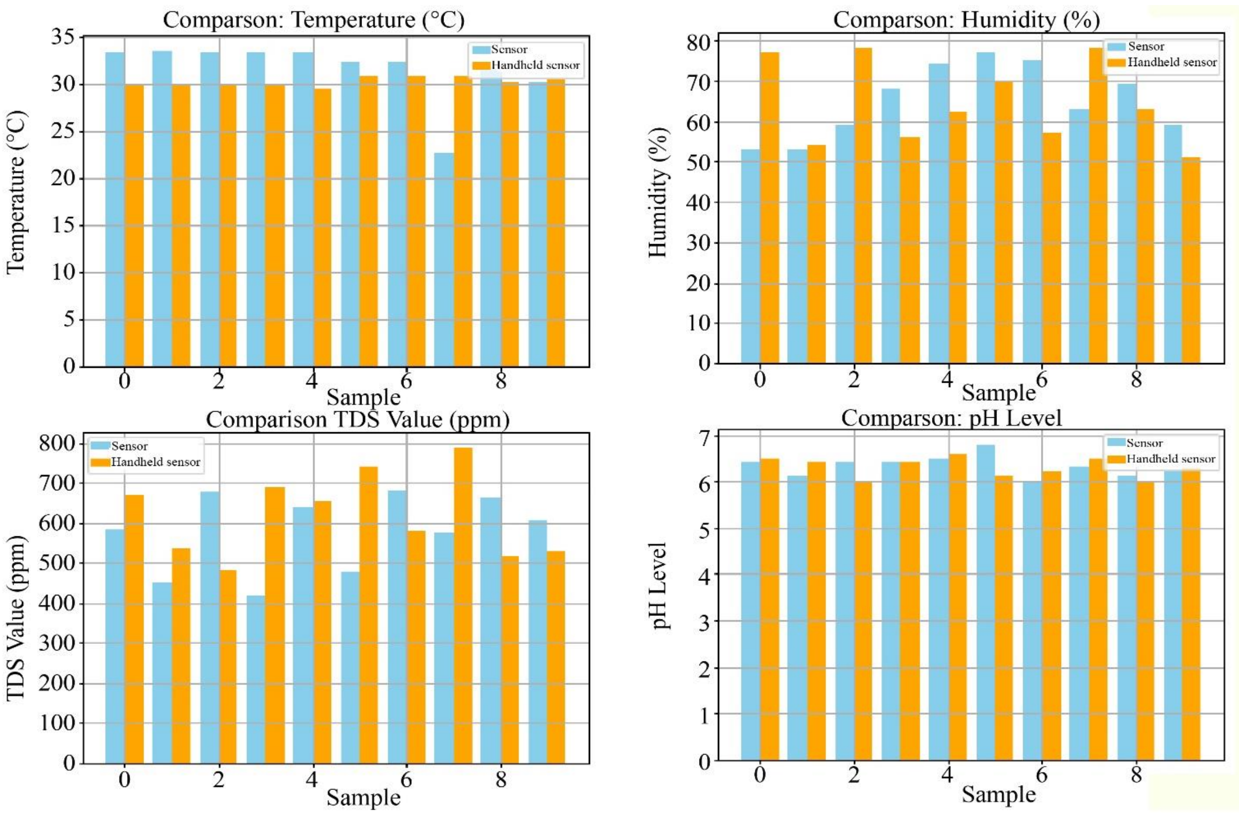

Fig. 14 Comparison of measurements

5.2. Results of the Impact of the System on Lettuce Cultivation in the NFT Hydroponic System

The system proved to be highly efficient in resource management, minimising water and nutrient wastage by 47.3%, as shown in Figure 16, and the result obtained through Equation (1), compared to traditional systems. This improvement is due to the precision of the sensors and the automated control of the system. In addition, its ability to operate autonomously allowed a significant reduction in manual intervention, translating into time and cost savings for producers. The stability of the nutrient solution, a critical factor in NFT systems that favored uniform and healthy plant development, was also highlighted. The results of the pilot test validate the feasibility of the system not only in technical terms but also in economic and environmental. Opportunities for improvement are also identified, such as integrating more sensors or predictive algorithms for even more advanced management. Overall, this reaffirms the potential of IoT systems applied to NFT hydroponics as a key tool for more sustainable and innovative agriculture.

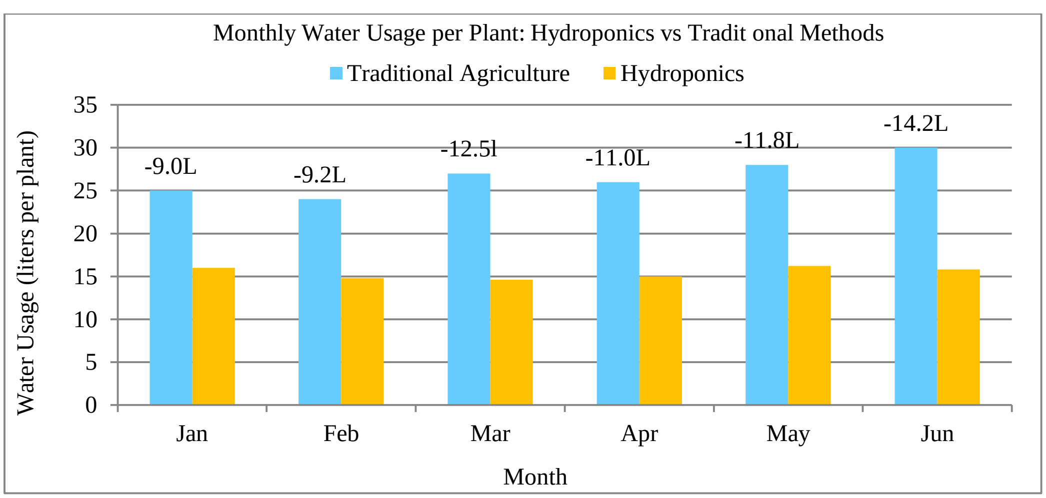

Fig. 15 Amount of water per month

$$Potential\ saving = \left(\frac{Traditional}{hydroponics}\right) x100 \quad (1)$$

5.3. Plant Development when Using the Monitoring System

The lettuces show green leaves of uniform size and no obvious signs of water stress or nutrient deficiency. This is evidence that the NFT system maintained an adequate nutrient solution and an environment conducive to plant growth.

The arrangement of plants in the channels ensures efficient use of space and nutrient solution, which is characteristic of the NFT design. This result confirms that the continuous and controlled flow of the nutrient film effectively provides water and essential minerals directly to the roots.

Fig. 16 Results of lettuce cultivation

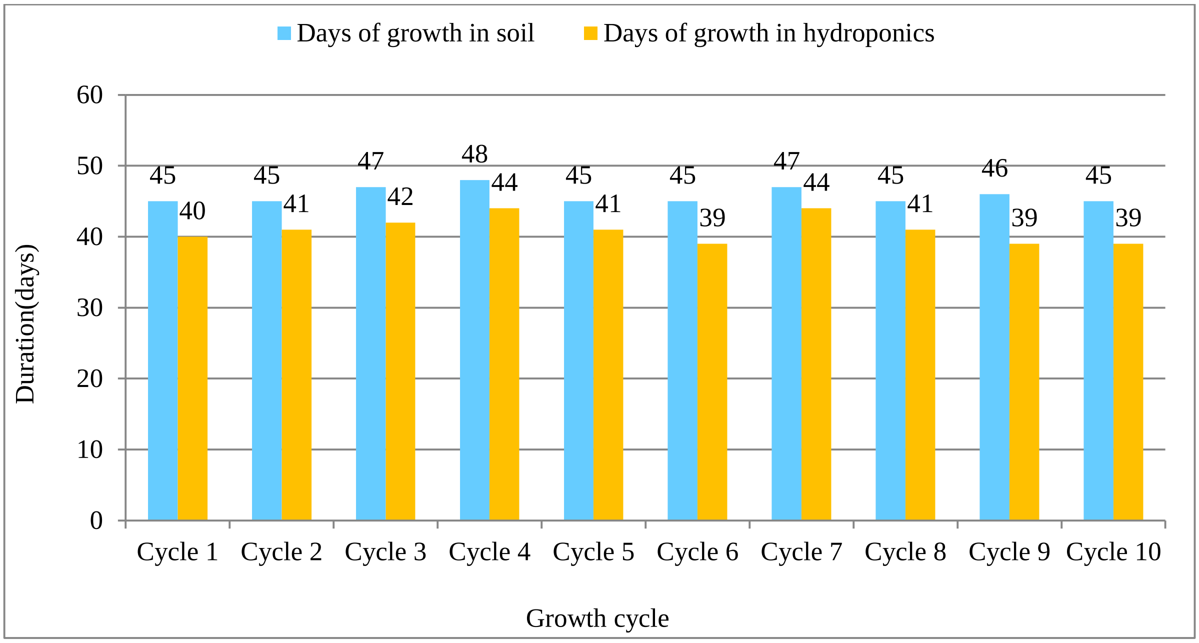

Fig. 17 Comparison between traditional cultivation and hydroponic cultivation

It is observed that growth in hydroponics is faster compared to traditional agriculture. This is because lettuces develop in a more controlled environment, which allows an average reduction of 7.5 days in the cultivation time, equivalent to 16.38% less. The average growth time in the soil is 45.8 days, while in hydroponics, it is 38.3 days. In addition, the standard deviation is 1.08 days in soil and 2.37 days in hydroponics, indicating a slightly greater variability in the latter method.

6. Discussion

Despite the success of the system, some limitations were identified. For example, while effective under ideal conditions, the system's reliance on wireless communication could fail in environments with interference or without stable coverage. In addition, the system could benefit from more advanced predictive algorithms that anticipate possible parameter deviations and take preventive actions. Another area for improvement is the robustness of the sensors in high-humidity environments and prolonged exposure to nutrient solutions. Although the selected sensors proved adequate for the pilot test, developing more robust and accurate devices could increase the durability and reliability of the system. In summary, the implementation of this hydroponic system not only demonstrates its technical efficiency and capacity to transform traditional agriculture towards a more intelligent and sustainable model. The results validate its use in lettuce crops and open the door to its application in various hydroponic crops.

Ideal crop growth is achieved with an optimum pH control between 5.5 and 6.5 and an electrical conductivity between 1400 and 2000 ppm. In the first sowing, we obtained results in 60 days, while in the second sowing, we managed to reduce the time to only 45 days, well below the usual in traditional crops in soil, where lettuce usually takes about 90 days to be ready for harvest. However, significant challenges remain in optimising the monitoring system, such as the deficiency of wireless communication channels in uncontrolled environments. In this context, artificial intelligence can significantly contribute to the study and the advancement of precision agriculture, especially through implementing LSTM models or other approaches oriented to the prediction of continuous values.

7. Conclusions

The monitoring system proved to be a useful tool in the field of agriculture, specifically in the monitoring of hydroponic lettuce cultivation. In which it was possible to identify an increase in temperature above the adequate conditions for lettuce. For this reason, it was proven that temperature is critical since some lettuce leaves were burned due to the large amount of sunlight received that afternoon. Likewise, it was proven that incorporating embedded systems allows for minimising costs and maximising versatility in information management. Due to its small size, its portability allows for better and more effective performance in developing specific applications through the different features and peripherals that various communication protocols can adopt. It is worth mentioning that the monitoring system implemented in the hydroponic cultivation was the substrate technique, which studied the possible sensors suitable for the conditions where they were going to be located if another type of technique were to be implemented, for example, the floating root technique, it is necessary to see what conditions the humidity and temperature sensors must meet for where they are going to be installed.

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