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Development of an IoT prototype for automated irrigation in sustainable agricultural greenhouses

Desarrollo de un prototipo IoT para la automatización del riego en invernaderos agrícolas sostenibles

Esp. Sergio Andrés Hurtado Vargas[1], **Esp. Diego Alejandro Gutiérrez Naranjo**[1], **MSc. Javier Eduardo Martínez Baquero**[1]

[1] **Universidad de los Llanos,** Facultad de Ciencias Básicas e Ingeniería, Especialización en Instrumentación y Control Industrial, Villavicencio, Meta, Colombia.

Correspondence: jmartinez@unillanos.edu.co

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Abstract: Precision agriculture requires technological solutions that optimize water use and improve the monitoring of environmental variables in protected cropping systems. This study presents the design, implementation, and validation of an Internet of Things (IoT)-based prototype for automatic irrigation monitoring and control in a greenhouse dedicated to cilantro (*Coriandrum sativum* L.) cultivation. The proposed architecture integrates an ESP32 microcontroller as the central processing unit, DHT22 and DHT11 sensors for temperature and relative humidity measurement, an Autonics TK4S PID controller for thermal regulation, a DS1302 real-time clock (RTC) module for scheduling irrigation events, and an embedded web server that enables system monitoring and configuration through a local wireless network without relying on cloud-based services. Experimental validation was conducted over a continuous 24-hour period under both controlled and representative operating conditions, with environmental data acquired every five minutes and stored on an hourly basis. The results demonstrated stable system performance, achieving 100% availability, a solenoid valve response time of less than one second, no communication failures, and successful execution of all scheduled irrigation events. Environmental variables remained within suitable ranges for cilantro cultivation, with temperatures between 23.3 °C and 23.6 °C and relative humidity values ranging from 80% to 84%. Furthermore, comparison with a conventional irrigation strategy showed a 25.2% reduction in water consumption, a 37.5% decrease in the number of irrigation events, and a 25% reduction in pumping time. These findings demonstrate the technical feasibility of the proposed IoT architecture as a cost-effective solution for improving water-use efficiency and automated environmental monitoring in protected agriculture systems.

Keywords: automation, greenhouses, internet of things, prototype, sustainable agriculture.

Resumen: La agricultura de precisión requiere soluciones tecnológicas que optimicen el uso del agua y mejoren el monitoreo de las variables ambientales en cultivos protegidos. Este trabajo presenta el diseño, implementación y validación de un prototipo IoT para el monitoreo y control automático del riego en un invernadero destinado al cultivo de cilantro

(*Coriandrum sativum* L.). La arquitectura propuesta integra un microcontrolador ESP32 como nodo central, sensores DHT22 y DHT11 para la medición de temperatura y humedad relativa, un controlador PID Autonics TK4S para el control térmico, un módulo RTC DS1302 para la programación horaria y un servidor web embebido que permite la supervisión y configuración del sistema mediante una red local inalámbrica, sin dependencia de servicios en la nube. La validación experimental se realizó durante 24 horas bajo condiciones controladas y representativas de operación, con adquisición de datos cada cinco minutos y almacenamiento horario de información. Los resultados evidenciaron un funcionamiento estable del sistema, con disponibilidad del 100%, respuesta de la electroválvula inferior a un segundo, ausencia de pérdidas de comunicación y ejecución correcta de todos los eventos programados. Las variables ambientales permanecieron dentro de rangos adecuados para el cultivo de cilantro, registrándose temperaturas entre 23,3 °C y 23,6 °C y humedades relativas entre 80% y 84%. Asimismo, la comparación con un esquema convencional mostró una reducción del 25,2% en el consumo de agua, una disminución del 37,5% en el número de eventos de riego y una reducción del 25% en el tiempo de bombeo. Los resultados demuestran la viabilidad técnica de la arquitectura IoT propuesta como una alternativa de bajo costo para mejorar la eficiencia hídrica y el monitoreo automatizado en sistemas de agricultura protegida.

Palabras clave: agricultura sostenible, automatización, invernaderos, internet de las cosas, prototipo.

1. INTRODUCTION

Growing water scarcity, rising food demand, and the effects of climate change have driven the development of smart systems to optimize the use of water resources in agriculture [1-2]. Although the Internet of Things (IoT) has proven to be a promising technology for crop monitoring and automation, its adoption by small and medium-sized producers remains limited due to implementation costs, dependence on communications infrastructure, and the complexity of many reported architectures [3].

Recent literature has described numerous IoT architectures designed for smart irrigation. Some studies focus primarily on the remote acquisition and visualization of environmental variables such as soil moisture, temperature, and light levels using wireless networks and cloud platforms, enabling real-time monitoring and historical data analysis [4].

On the other hand, cilantro (Coriandrum sativum L.), also known as coriander, is an annual herbaceous plant (meaning it completes its life cycle in a single year), which has generated significant interest in agricultural production systems. However, various studies have confirmed that high temperatures trigger a very common phenomenon called bolting or premature flowering, which results in a reduction in its commercial value along with changes in its flavor [5].

Other studies incorporate automated control algorithms to optimize water supply and even integrate artificial intelligence and renewable energy, achieving significant improvements in water and energy efficiency [6-7].

Similarly, architectures based on Raspberry Pi, ESP32, LoRa, and LoRaWAN have been reported that facilitate the connectivity of distributed sensors and the monitoring of agricultural greenhouses.
Its global significance is evident in practices found in countries such as Israel, Spain, and Australia, which serve as examples of this. Nevertheless, coordinated support through public policies is required, along with clear communication regarding risks and international collaboration, starting with developing countries [8].

In the field of agriculture, one can find Traditional Irrigation Systems (TIS), which consist of a socio-technical-ecological structure and are part of ancient and complex hydro-social systems—water management infrastructures that have been maintained over the centuries. Based on the study of various empirical cases, it is argued that specific cultural, social, and economic contexts influence decision-making processes related to access to resources [9-10].

Initially, one might conclude that the implementation of automated systems depends solely on the availability of resources for the irrigation system, but in Colombia, the reality is very different. Emphasis is placed on small-scale farmers, who account for 70.8% of total agricultural production—a significant figure— however, only 2.4% have access to this new technology known as the IoT. Of course, alternatives have been developed to address these factors, through open-access platforms such as LoRa and LoRaWAN (Long Range Wide Area Network), with the municipality of San Cristóbal playing a leading role [11].

This low adoption of innovation is also evident in Colombia's Caribbean region due to the country's agricultural context, which is characterized by traditional irrigation methods; however, 93% of the country's eggplant production comes from this region, indicating a limited level of technological advancement [12].

Along the same lines, a study conducted in Sesquilé, Cundinamarca, evaluated the controlled deficit irrigation (CDI) strategy in pear crops, demonstrating that it is possible to significantly reduce water application without compromising yield or fruit quality. The results revealed osmotic adjustment mechanisms in the plants, which allowed them to cope with water stress during fruit growth without affecting productivity [13].

These limitations represent a significant technological gap for precision agriculture, especially in contexts where digital infrastructure is limited and cost-effective, reliable, and easily scalable solutions are required. Consequently, there is a need to develop IoT architectures that integrate data acquisition, automatic control, historical data storage, intelligent alarm management, and local monitoring without relying on external services, thereby ensuring operational continuity and ease of implementation [14–15].

In this regard, it has been shown that, given the thermal conditions—particularly soil factors and specific time periods, such as the afternoon—temperature plays a decisive role in crop development, with ranges between approximately 28°C and 32.5°C contributing to proper growth [16].

Despite the reported advances in IoT systems for precision agriculture, most research focuses on the remote monitoring of environmental variables or the automation of specific functions, often relying on cloud platforms, permanent communications infrastructure, or high-cost architectures that limit their adoption by small and medium-sized producers.

Furthermore, there are few studies that integrate, within a single architecture, real-time monitoring, automatic irrigation control, local data storage, alarm management, event traceability, and an embedded web interface that operates autonomously on local networks. In this context, the research problem consists of determining how to develop a low-cost IoT architecture that enables the optimization of irrigation in agricultural greenhouses through the reliable integration of sensors, actuators, control algorithms, and monitoring tools, without relying on external connectivity services [17].

For this reason, in cities with humid or hot climates—such as Villavicencio (Colombia)—a major challenge arises due to the high temperatures, which influence the growth patterns of cilantro. Consequently, this study proposes and implements a functional prototype that aims to bridge this technological gap by providing a scalable, autonomous solution adaptable to the conditions of small-scale farmers, enhancing water use efficiency and facilitating the adoption of precision agriculture technologies in resource-constrained contexts, with the aim of overcoming the limitations identified in previous studies through an autonomous, low-cost, and easily replicable architecture designed to optimize water use and facilitate the adoption of precision agriculture technologies by small and medium-sized producers.

2. METHODOLOGY

In order to develop an automated prototype for irrigation in agricultural greenhouses, we employ a methodology that combines observation and analysis of various natural phenomena within the structure, thereby implementing variable controls that allow us to verify the cause-and-effect hypothesis, through a network of stages that begins with in-depth research, followed by the determination of technical (design, assembly, and programming) and agricultural criteria, ultimately resulting in the development of an IoT system.

The stages carried out are detailed below.

2.1. Literature review

The literature review analyzed recent scientific articles on precision agriculture, smart irrigation, the Internet of Things (IoT), and greenhouse automation, which made it possible to identify technologies, architectures, sensors, protocols, and control strategies, as well as to identify the research gap, the technical problem, and the criteria that guided the prototype's design.

2.2. Technical and agricultural parameters

The project's technical and agricultural parameters were defined based on the requirements of greenhouse cultivation and the conditions necessary to ensure efficient water use. From a technical standpoint, the architecture was based on an ESP32 board as the central processing unit, DHT11 and DHT22 sensors for monitoring temperature and humidity, a DS1302 RTC module for scheduling, a relay system to activate the solenoid valve, and an embedded web interface for local monitoring and configuration.

In addition, mechanisms for persistent storage, historical logging, and alarm management were implemented. In the agricultural sector, temperature and humidity thresholds and irrigation schedules were established in accordance with the needs of greenhouse crops, with the aim of maintaining stable environmental conditions, optimizing water consumption, promoting the physiological development of plants, and facilitating the experimental validation of the prototype under controlled conditions.

2.3. IoT System Design and Development

Below are the design and 3D drawings of the automated irrigation system, created using SolidWorks. Fig. 1 shows the 3D design of the greenhouse.

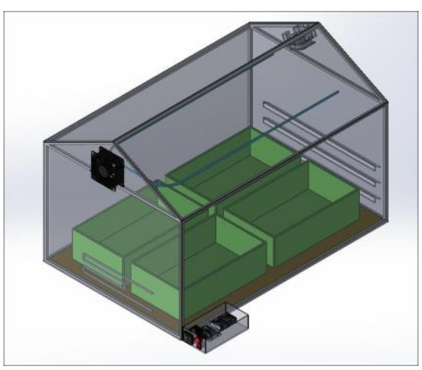
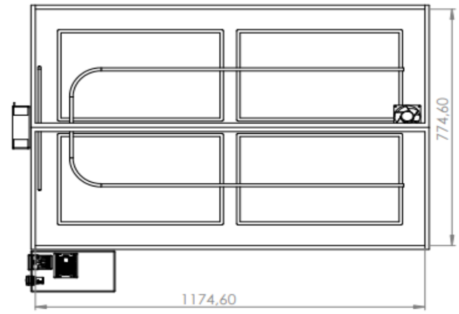
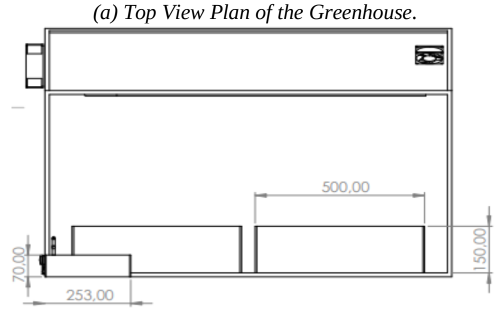


Fig. 1. *3D Design of the Greenhouse.*

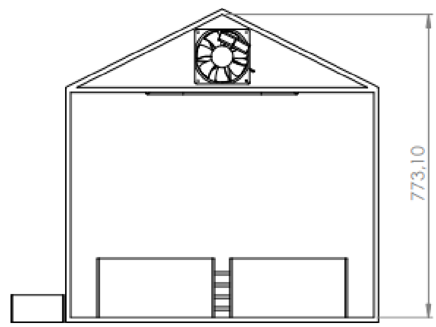
Fig. 2 shows the surfaces of the proposed sketch, including front, side, and top views. The purpose of these views is to provide a clear visualization of the prototype's geometry, aiding in the understanding of the dimensions, spaces, and location of the components.



(a) Top View Plan of the Greenhouse.



(b) Side View Plan of the Greenhouse.



(c) Front View Plan of the Greenhouse.
Fig. 2. *Greenhouse Blueprints.*

2.3.1. Assemblies and Connections

With the design finalized, we proceed to assemble the structure, as shown in Fig. 3, and connect the sensors and actuators, as shown in Fig. 4.

Fig. 3*. Assembled Structure of the Greenhouse Prototype.*

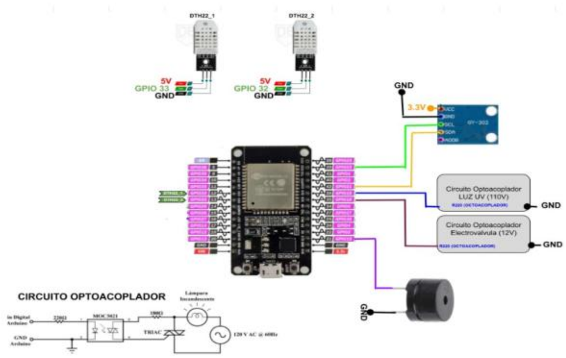


Fig. 4 *Schematic Diagram of the Automatic Irrigation System (Sensors and Actuators).*

The instrumentation system consists of a DHT22 sensor installed in the main area of the greenhouse due to its higher accuracy (±0.5 °C and ±2% RH) for the continuous monitoring of critical environmental variables, while DHT11 sensors were used in secondary modules designed to monitor local crop conditions. The time reference is provided by a DS1302 RTC module with a backup battery, ensuring the continuity of the schedule even when the system is disconnected from the power supply.

2.3.2. Interface and Communications

The prototype greenhouse monitoring and irrigation system was implemented using an ESP32 board, which serves as the central hub for processing and transmitting data. Therefore, the system was developed using the Arduino IDE, employing a variety of libraries that handle communication with sensors, transmission modules, and data reception. Given the assigned pins, temperature, humidity, and light intensity sensors were added, which provide key information for the system's operation. The following models were used: a DHT11 sensor and a DHT22 sensor for monitoring environmental variables.

To manage time and schedule events, a real-time clock (RTC) adapter based on the DS1302 integrated circuit was used. This device is designed to maintain a database of the date and time, which is essential for setting irrigation and lighting schedules within the system.

In addition, a relay is incorporated as an actuator to activate irrigation via the solenoid valve. Its behavior depends on two key factors: first, environmental conditions; and second, the specified programming logic (conditions). Fig. 5 shows the program's flowchart in the Arduino IDE.

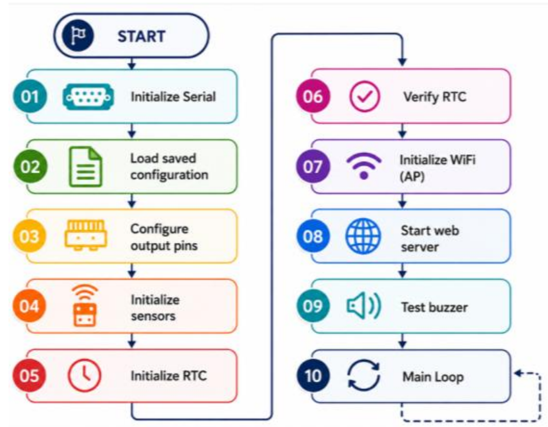


Fig. 5. *Program Flowchart in the Arduino IDE.*

For the IoT connection, the ESP32 was configured as an access point, which allows it to establish an independent local network—an advantage for users, as they can connect directly from any device without having to remain connected to the internet.

Similarly, the display and control of variables were integrated into the web server—created using the WebServer library—enabling access via a web browser for real-time monitoring. It is worth noting that the communication protocols between the web interface and the system are specifically based on HTTP (Hypertext Transfer Protocol), and the data is formatted in JSON (JavaScript Object Notation).

Incidentally, the goal is to make use of the data collected through a storage system; therefore, the Preferences library is used to apply temperature and humidity thresholds and schedules, thereby preventing data loss when each process resumes.

To keep a record of irrigation events, a structure called `WaterEvent` is defined, which tracks each irrigation cycle, allowing the date, exact start time, and irrigation duration in milliseconds to be saved. Its importance lies in the traceability it enables in agricultural IoT projects. Among the features of the web platform, the alarm system stands out due to the AlarmState evaluateAlarms() function. Its primary task is to analyze all sensors to determine the system's status, sending alert messages to indicate normal operation or whether the system has entered an alert, critical, or sensor failure phase.

Finally, automatic irrigation control depends on environmental conditions defined as thresholds; the user can select settings based on emerging needs. Fig. 6 shows the flowchart of the irrigation system.

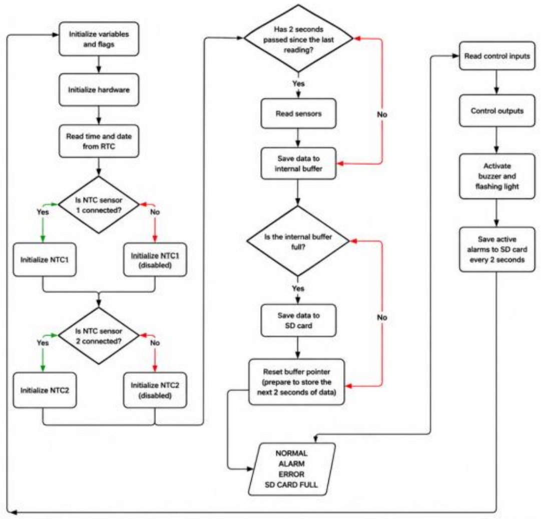


Fig. 6. *Irrigation System Flowchart.*

For the communication diagram of the greenhouse prototype, shown in Fig. 7, the various functions were defined: the ESP32 serves as the central node, acquiring data from the humidity and temperature sensors and then controlling the solenoid valve, which acts as the system's actuator. Through a Wi-Fi connection, users can connect to the embedded web server to monitor the system in real time and make adjustments to the project using the web interface [18].

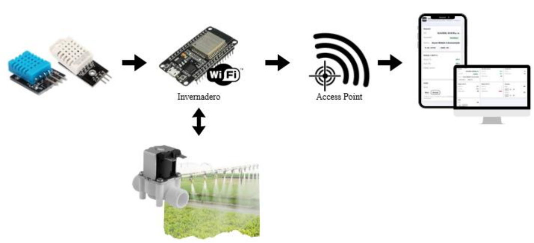


Fig. 7. *Data Communication Diagram and IoT Interface*

2.3.3. PID Control

PID control is widely used in industry because its architecture and implementation offer great versatility and ease of use. Furthermore, it is very common to find systems of this type in 95% of control loops, since their performance depends entirely on the interplay of its three parameters: the proportional, integral, and derivative gains.

There are two ways to configure the criteria in a PID controller: the first is model-based, meaning it focuses on identifying the structure and thresholds of the controlled plant to optimize it, but this can be time-consuming and may not yield the expected results; the second is data-driven, requiring only the system's input and output information to determine the controller's limitations without explicitly needing a model [19]. Equation (1) corresponds to the PID controller.

$$u(t) = Kpe(t) + \frac{Kp}{Ti}\int e(t)dt + KpTd\frac{d}{dt}e(t) \qquad (1)$$

2.3.4. TK4S Temperature Controller Setup

To control the temperature inside the greenhouse, the high-performance Autonics TK4S PID digital controller is used with a Type K thermocouple to record the data. However, to obtain a reading, the controller must first be configured according to the manual, which specifies the pin connections to which the thermocouple must be connected; in this case, pins 11 and 12 are used, as shown in Fig. 8 [20].

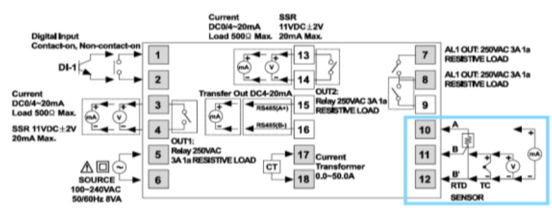


Fig. 8. *TK4S Manual for Electrical Connections Between the TC and the Controller.*

Next, configure the system using the parameters—specifically parameter number three—to set up the equipment for thermocouple operation. Table 1 below lists the restrictions.

Table 1: *Specifications of the Autonics TK4S Digital Controller*

Parameter 3	
Indicator	**Set value**
Entry type	K
Unit	°C
Offset	0 °C
Output Control	H - C
Control Type	P.P
Outoput 1	SSR (Heat)
Output 2	SSR (Cooling)
Preheating Time	10.0 s
Time Control Refrigeration	10.0 s

After setting the thresholds in the controller, proceed to perform auto-tuning on the Autonics TK4S device (using parameter two). Set the setpoint to twenty-nine and record the resulting parameters in Table 2.

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Table 2: *PID controller parameters using the auto-tuning method.*

	Parameter 2	
Controller	**Heating Value**	**Cooling Value**
P	0,9	0,9
I	117	117
D	24	24

Once the controller parameters have been set as described in the previous section, Fig. 9 shows the step response of the PID control system.

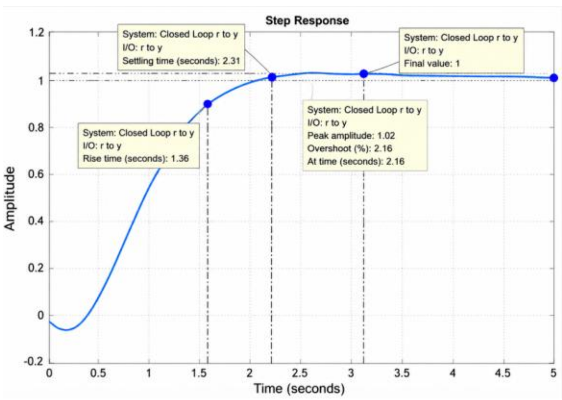

Fig. 9. *Step Response of the PID Controller*

2.4. Validation

The prototype validation was carried out in two complementary stages. In the first stage, tests were conducted under controlled conditions inside the experimental greenhouse, where it was possible to modify environmental variables to verify the individual operation of the sensors, actuators, control algorithms, and monitoring platform.

Subsequently, the system was evaluated under representative operating conditions, keeping the prototype in continuous operation for 24 hours, with environmental data acquired every five minutes and historical records stored every hour. This procedure allowed for an analysis of the stability of the measurements, the availability of the embedded web server, the reliability of wireless communication, and the system's automatic response during a complete operating cycle without user intervention.

The controlled conditions consisted of simulating different operating scenarios, including changes in temperature, variations in relative humidity, and the intentional disconnection of sensors to verify the behavior of the control algorithm and the alarm system. In contrast, the representative operating conditions corresponded to the prototype's normal operation, where irrigation decisions were executed automatically based on user-configured thresholds and the schedule stored in the system.

Fig. 10 shows the implementation of the data monitoring system, in which the user experience is divided into the following stages.

The general section displays the overall system status within the main interface and includes a live summary with data containing relevant information about the sensors and the control system. The clock is synchronized in real time (RTC), supporting the data history. The interface displays temperature and humidity readings for different zones simultaneously: the main section of the greenhouse, monitored by the DHT22 sensor, and the two remaining reference modules, each equipped with a DHT11 sensor.

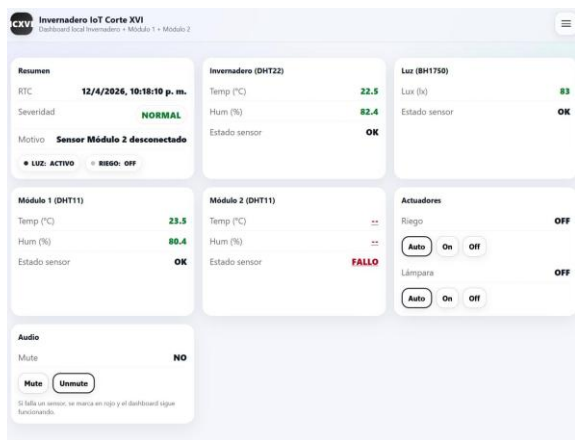

Fig. 10. *General interface of the IoT program for controlling the irrigation system*

Data collection occurs periodically based on the defined time interval, after which the data is processed and displayed with precision down to the decimal place. In addition to monitoring the variables, the system provides a guide that outputs two possible sensor states (OK/FAIL), in the event that communication is lost; this is an industrial-grade version designed to detect faults so as not to compromise the overall operation of the system. The system frequently evaluates the defined thresholds to activate its actuator—in this case, the lamp—applying control strategies.

3. RESULTS

For actuator control, the system includes a control feature that supports both manual and automatic operation of the actuators; Through the digital platform, where the user can choose between the "Auto," "On," and "Off" options, the functionality of these modes is highlighted; for example, in automatic mode, activations are based on the environment and specific schedules, while in manual mode, the customer has direct control.

An alert system controlled via a buzzer module is integrated, with the alert level determined by the severity detected by the system; Additionally, the interface allows users to enable or disable the signal, providing greater flexibility in its use across different environments; these settings ensure that alarms are triggered based on the system's current status and the defined time settings.

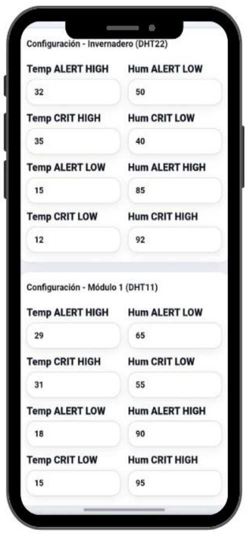

Fig. 11. *Threshold Configuration Interface for Irrigation System Control.*

In addition, an alarm signal has been added that, through a status categorization system, will issue alerts based on their severity and in relation to established thresholds; to this end, a function was used that evaluates the alarms to facilitate interpretation of the system's operation. It should be emphasized that the system itself indicates the reason for its current condition, as seen in the case of Module 2, which has a sensor disconnection, as shown in Fig. 11.

As a point of reference, it can be seen that the greenhouse system demonstrates robust flexibility in the collection, analysis, and sampling of real-time data; the addition of sensors and actuators, in conjunction with the central web server, demonstrates the feasibility of pioneering local IoT solutions without the need for a cloud connection.

Fig. 12 shows the graphs depicting changes in temperature, humidity, and light level recorded over a 24-hour period at a rate of one data point per hour, in accordance with the structure implemented in the design. This storage-focused approach aims to analyze trends without filling the microcontroller's memory, as previously established in the programming through its historical log.

The temperature graph shows a noticeable difference between the two measurement points: the greenhouse (GH) and Module 1 (M1). The main sensor (DHT22) shows stable readings with a slight variation, fluctuating only slightly within the range of 23.3°C to 23.6°C, which is consistent with its high precision. In contrast, the DHT11 module shows a more noticeable variation, which may be due to its specific location within the greenhouse. The low variation in the data indicates that the system maintains a partially stable thermal condition; this behavior is as expected given the implemented control logic.

Now, regarding humidity, it is divided into two distinct levels that are clearly differentiated as follows: the DHT22 sensor readings fluctuate around 84%, while those from Module 1 are closer to 80–83%. Clearly, this categorization suggests a tendency for humidity to build up within the system, due to the irrigation spray and the operation of the fans. The fluctuations observed have a low amplitude, from which it can be inferred that the changes occur gradually in accordance with the programmed control logic.

Fig. 12. *Variation in Environmental Variables.*

Finally, the results obtained show that the assembled model correctly collects data, clearly representing the greenhouse's critical variables. The stability of the temperature and humidity findings is validated through sensor readings (readSensors()), historical data storage (pushHistory5m() and maybeStoreHourSample()), and, in short, the integration of the control system.

The differences between devices such as temperature sensors highlight the potential technical limitations or constraints that may arise; in this case, the DHT11 sensor compared to the DHT22, where accuracy and reliability tend to be a drawback. As a result, this data evaluates the implemented structure and verifies its applicability in IoT systems focused on precision agriculture.

The results show that the developed architecture maintains stable operation throughout the experimental cycle, reducing unnecessary activations of the irrigation system, improving water use, and ensuring continuous local monitoring through the embedded web interface. Table 3 shows the performance indicators for the IoT system.

***Table 3:** IoT System Performance Metrics.*

Indicator	Value obtained
Validity Period	24 h
Acquisition interval	5 min
Stored Records	288
System Availability	100 %
Properly Executed Irrigation Events	100 %
Average response time of the solenoid valve	< 1 s
Temperature error (DHT22)	±0.5 °C
Humidity error	±2 % HR
Loss of communication	0 eventos
Alarms Detected Correctly	100 %

Table 4 presents a comparison of water consumption.

***Table 4:** Comparison of Water Consumption.*

Variable	Conventional Irrigation	System IoT	Indicator
Water used (L/day)	42.5	31.8	↓ 25.2 %
Water Conservation (%)	—	25.2	Regarding the conventional one
Number of irrigation events	8	5	↓ 37.5 %
Total pumping time (min/day)	72	54	↓ 25.0 %

Water savings are calculated using equation (2).

$$\text{Water saving (\%)} = \frac{Vconv - VIoT}{Vconv}\, x\, 100\% \quad (2)$$

The main scientific contribution is an integrated ESP32-based IoT architecture that combines real-time monitoring, automatic irrigation, historical data storage, alarm management, and an embedded web server—all without relying on the cloud. Its scalable, reliable, and low-cost design enhances precision agriculture for small-scale farmers.

The use of an embedded web server, local storage, a dedicated wireless network, and off-the-shelf electronic components eliminates dependence on external platforms, reduces operating costs, and facilitates the replication of the system in various protected agriculture settings.

4. CONCLUSIONS

An IoT prototype was designed and implemented for the automatic monitoring and control of irrigation in a greenhouse, integrating environmental sensors, an ESP32 microcontroller, a PID controller for temperature regulation, local data storage, and an embedded web server for remote monitoring and configuration. Experimental tests conducted during a continuous 24-hour cycle demonstrated the stable operation of the proposed architecture, with 100% system availability, no communication losses, and correct execution of scheduled events.

The experimental results showed that the system maintained stable environmental conditions during the evaluation period, recording temperatures between 23.3 °C and 23.6 °C and relative humidity levels between 80% and 84%—values consistent with the recommended ranges for growing cilantro under protected agriculture conditions. Furthermore, the use of the DHT22 sensor yielded more stable measurements than those provided by the DHT11 sensors, confirming the influence of instrument accuracy on the performance of the monitoring system.

A comparison with a conventional irrigation system showed a decrease in the volume of water supplied, a reduction in the number of irrigation events, and a shorter cumulative operating time for the pumping system—results that support the potential of IoT architecture to optimize water resource management in small-scale greenhouses. However, these results apply exclusively to the experimental conditions evaluated and do not allow for generalizing the system's performance to other crops, production scales, or climatic conditions without conducting additional validation processes.

Among the main limitations of the study are the duration of the experimental validation, which was restricted to a 24-hour period; the evaluation of a single crop; and the lack of long-term testing under different seasonal and operational conditions. Consequently, the scope of the proposed solution is limited to demonstrating the technical and functional feasibility of a low-cost IoT architecture for automated irrigation monitoring and control. For future work, it is recommended to conduct longer-term experimental campaigns, incorporate soil moisture and flow sensors to directly quantify water use efficiency, and validate the system in larger-scale greenhouses with different crop species.

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