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# Intelligent automated monitoring and control system with iot for climate management and irrigation in greenhouses

# Sistema inteligente de monitoreo y control automatizado con iot para la gestión del clima y riego en invernaderos

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**INNOVACIÓN Y CONVERGENCIA: IMPACTO MULTIDISCIPLINAR**

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## Abstract

This project presents the design of an intelligent monitoring and automated control system with IoT to optimize climate and irrigation management in greenhouses. The system integrates temperature, humidity, light, CO2 and soil moisture sensors, processing the data through an ESP32 microcontroller. The user interface, implemented through the Blynk and ThingSpeak platforms, allows remote monitoring and manual or automatic control of the greenhouse. The system incorporates drip irrigation and misting, dynamically adjusting to soil and environmental conditions. Programming includes automatic and manual modes, with hysteresis and timer functions to optimize actuator operation. Economic analysis demonstrates the feasibility and cost-effectiveness of the system, with a positive return on investment in the short term. This low-cost solution, based on ESP32 technology, offers an affordable alternative for small farmers, improving resource efficiency and increasing agricultural productivity in controlled environments.

**Keywords:** Smart greenhouse; IoT; Agricultural automation; Sustainable agriculture; Efficient irrigation.

## Resumen

Este proyecto presenta el diseño de un sistema inteligente de monitoreo y control automatizado con IoT para optimizar la gestión del clima y riego en invernaderos. El sistema integra sensores de temperatura, humedad, luz, CO2 y humedad del suelo, procesando los datos mediante un microcontrolador ESP32. La interfaz de usuario, implementada a través de las plataformas Blynk y ThingSpeak, permite el monitoreo remoto y el control manual o automático del invernadero. El sistema incorpora riego por goteo y nebulización, ajustándose dinámicamente a las condiciones del suelo y ambientales. La programación incluye modos automático y manual, con funciones de histéresis y temporizadores para optimizar el funcionamiento de los actuadores. El análisis económico demuestra la viabilidad y rentabilidad del sistema, con un retorno de inversión positivo a corto plazo. Esta solución de bajo costo, basada en tecnología ESP32, ofrece una alternativa accesible para pequeños agricultores, mejorando la eficiencia en el uso de recursos y aumentando la productividad agrícola en entornos controlados.

**Palabras clave:** Invernadero inteligente; IoT; Automatización agrícola; Agricultura sostenible; Riego eficiente.

## Introduction

Greenhouses play a very important role in modern agriculture, allowing the controlled cultivation of plants in protected environments (Endo et al., 2023). However, the efficient management of environmental conditions within these spaces represents a significant challenge for growers (Arka & Gritta, 2023). The lack of automated systems for monitoring and controlling variables such as temperature, humidity, light, and irrigation can result in suboptimal conditions for plant growth, which in turn can lead to disease, fungal proliferation, and decreased production efficiency (Mallareddy et al., 2023; Salihi & Himatkhwah, 2024).

In response to this problem, this paper focuses on the design of an intelligent monitoring and automated control system based on IoT (Internet of Things) technology to improve climate and irrigation management in greenhouses (Suvorin & Kabachiy, 2024). The overall objective of this study is to develop a technological solution that optimizes environmental conditions for plant growth, improves resource use efficiency and increases agricultural productivity in controlled environments (Leena Bharat Chaudhari, 2024; Yadav et al., 2025).

The rationale for this study is based on the growing need to adopt more affordable and efficient technologies for greenhouse agriculture, especially in urban areas with limited resources (Polycarpou, 2005). The integration of sensors, microcontrollers and actuators, together with IoT platforms, allows real-time monitoring and precise control of important environmental variables (Faouzi et al., 2017; Fullen & Catt, 2014). This approach not only improves the productive efficiency and profitability of smallholder farmers, but also contributes to the sustainability of agricultural production (Rokade et al., 2024).

The methodology employed in this project combines quantitative and analytical approaches (Mostafa et al., 2024). It starts with an assessment of the current state of a model greenhouse, followed by the determination of specific technical needs (Zheng et al., 2023). Subsequently, the architecture of the monitoring and control system is designed, including the selection of hardware and software components (Ardiansah et al., 2022). The system integrates temperature, humidity, light, CO2 and soil moisture sensors, processing the data using an ESP32 microcontroller (Awang Bono, 2024; Kamlesh Kalbande, 2023). The user interface, implemented through the Blynk and ThingSpeak platforms, allows remote monitoring and manual or automatic control of the greenhouse (Tooprakai et al., 2024).

The system incorporates drip irrigation and misting, dynamically adjusting to soil and environmental conditions. Programming includes automatic and manual modes, with hysteresis functions and timers to optimize actuator operation (He & Kang, 2024). In addition, an economic analysis is performed to demonstrate the feasibility and cost-effectiveness of the system, with a focus on short-term return on investment (R et al., 2024).

This study not only seeks to improve agricultural productivity and reduce resource consumption, but also aims to provide a valuable tool for research and teaching in agricultural sciences (Gulyamov, 2024). The proposed solution, based on low-cost ESP32 technology, offers an affordable alternative for small-scale farmers, thus contributing to the democratization of advanced agricultural technology (Akhigbe et al., 2021; Paradkar et al., 2023).

## Materials and Methods

The study has a descriptive-experimental approach for the collection and analysis of data to identify variables in the design of automated monitoring and control systems, evaluating the behaviors that affect the greenhouse based on temperature, humidity, light and CO2.

The core component of the system was the ESP32 microcontroller, chosen for its integrated WiFi and Bluetooth connectivity capabilities, as well as its wide compatibility with I/O interfaces. For environmental monitoring, specific sensors were used: the DHT22 to measure air temperature and relative humidity, the BH1750 for light intensity, the MH-Z19C for CO2 concentration, and a capacitive soil moisture sensor. Actuators included exhaust fans, electric heaters, foggers, drip irrigation systems, solenoid valves, and LED grow lights. The methodology applied in the section of this experimental research is quantitative-analytical which is used to collect and analyze numerical data from IoT sensors in an automated greenhouse control system, allowing to regulate environmental variables such as temperature, humidity and light and through the analytical method examines how the controlled environmental conditions affect agricultural production, evaluating the improvement in the quality and quantity of crops after the implementation of the system.

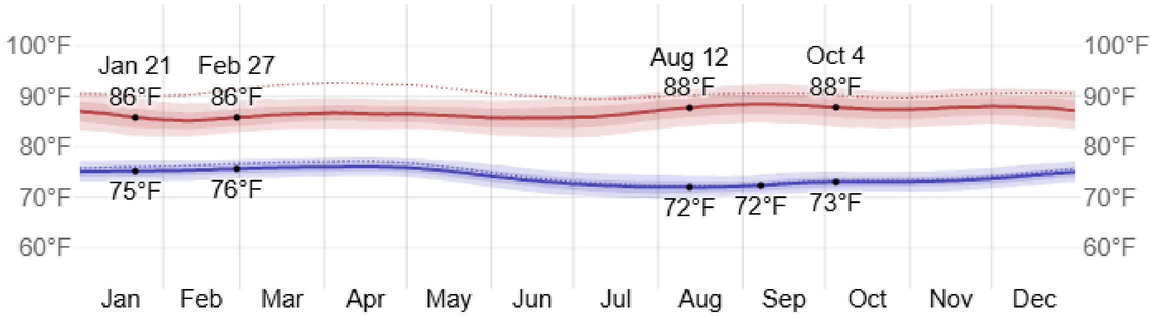
The procedure to carry out the monitoring and control design has been divided into four phases. In the first phase, the current state of the greenhouse is evaluated. The second phase addresses the technical needs of the greenhouse. The third phase focuses on the structure of the monitoring and control system design. Finally, in the fourth phase, the devices available on the market that best suit the project requirements are selected.

**Phase 1: Evaluation of the current state of the greenhouse**

As can be seen in Figure 1, the temperature in Quevedo reveals a moderate seasonal variation. Minimum temperatures remain relatively constant between 22°C and 24°C throughout the year, while maximum temperatures vary from 30°C during the cool period (January-February) to 31°C in the warm season (August-October) (Weather Spark, 2023).

This stability in minimums, combined with moderate peaks in maximums, suggests that the climate control system in the greenhouse should focus primarily on temperature regulation during the hottest periods, with minimal need for heating and a focus on efficient cooling and ventilation strategies.

**Figure 1.** Temperature behavior in the Quevedo canton




**Fuente:** Weather Spark, 2025

**Phase 2: Determining the technical needs of the greenhouse**

The greenhouse is a valuable resource for the agronomy educational community, serving as a laboratory for the study of various plant species under different conditions and treatments. Its location in a tropical climate and the current manual irrigation system make it particularly useful for research. Among the most common crops grown in this space are tomatoes, cucumbers, beans, cocoa and peppers, each with its own specific climate and care requirements.

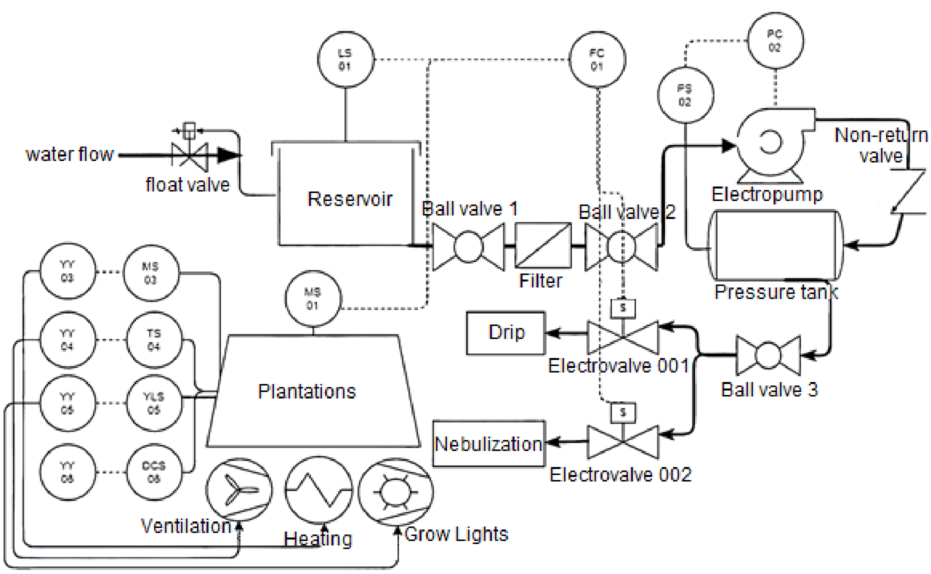
Tomato, for example, thrives in a moderate climate with daytime temperatures between 20 and 25 °C, and night temperatures between 10 and 17 °C. This crop requires precise water management to avoid water stress. Maintaining a relative humidity of 65-70% is crucial to prevent fungal diseases, which underlines the importance of a balanced environment for its optimal development (Allende et al., 2017). In contrast, cucumber is better adapted to warm, humid climates, tolerating a wider temperature range of 15-33 °C. This crop needs fertile soils with good drainage and a constant water supply, especially during flowering and fruit development. A relative humidity between 50-70% favors vigorous growth (Martínez, 2024).

Cocoa, on the other hand, is adapted to higher temperatures, between 22 and 30 °C, and requires a high relative humidity of 80-100% for optimal development. However, it is important to keep humidity below 85% to reduce the risk of disease. Finally, bell pepper prefers warm and temperate climates, with optimum temperatures between 20 and 25 °C. This crop needs well-drained soil and at least 6 hours of direct sunlight per day. A relative humidity of 50-70% is ideal to maintain a favorable environment and prevent diseases during growth (Mendoza, 2012).

### Phase 3: Monitoring and Control System Architecture

Figure 2 shows the P&ID diagram of the system reveals a process that integrates irrigation and climate control. Water is supplied to a reservoir through a float valve, with a level sensor (LS-01) for monitoring. The irrigation system operates through a pressure tank fed by an electric pump, controlled by flow (FC-01) and pressure (PS-02) sensors and ball valves. Irrigation is distributed by drip or misting, controlled by solenoid valves (001 and 002), while climate management is achieved with ventilation, heating and grow lights, regulated by actuators (YY-03 to YY-08) and soil moisture sensors (MS-01, MS-03, TS-04, YLS-05, DCS-06) in the plantations.

**Figure 2.** P&ID diagram of the system

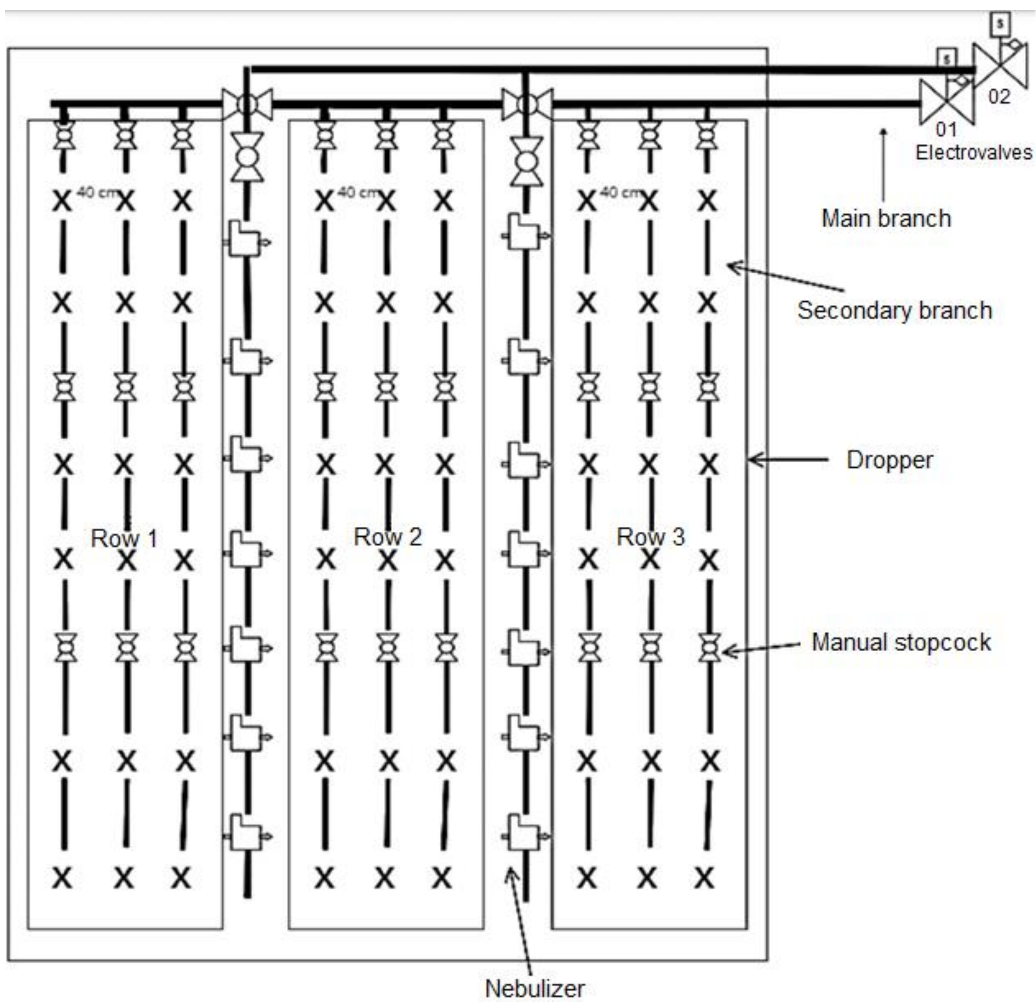



**Fuente:** Autores, 2025

## Diagram of the irrigation system

According to Figure 3, the greenhouse irrigation system is configured with a main branch that feeds three rows of crops. Each row receives water through a secondary branch and is irrigated through drippers evenly spaced, approximately every 40 cm, complemented by nebulizers at the end of each row to control environmental humidity. The system allows automated control through solenoid valves (01 and 02) in the main branch and manual adjustment through stopcocks in each secondary branch, optimizing water distribution for the specific needs of each crop.

**Figure 3.** Irrigation system of the greenhouse




**Fuente:** Autores, 2025

**Phase 4: Selection of devices from the market**

A wide variety of commercial components were found, which will be detailed below.

**Monitoring system**

A variety of sensors will be explored as shown in Table 1, highlighting some characteristics such as their functionality, practical applications and important considerations for the development of the project (Amaya, 2021).

**Table 1.** Sensors selected for the monitoring system

| Sensor | Type | Output | Range | Accuracy | Price |
|---|---|---|---|---|---|
| DHT11 | Temperature and Humidity | Digital | 0-50°C | ±2°C, ±5% HR | $2 |
| BH1750 | Light intensity | Digital (I2C) | 1-65535 lx | 1 lx | $2.50 |
| MH-Z19B | CO2 | (UART) | 0-5000 ppm | ±50 ppm + 5% | $25 |
| Capacitive Soil | Capacitive | Analog | 0-100% humidity | --- | 3.5 |

**Fuente:** ALLDATASHEET, 2025

The DHT11 sensor is considered a favorable option due to its low $2 cost, making it ideal for projects with limited budgets. While its accuracy of ±2°C and ±5% RH is lower compared to other sensors, its digital output simplifies integration with microcontrollers, and its 0-50°C range may be sufficient for general greenhouse monitoring, prioritizing cost-effectiveness over maximum accuracy. (Cevallos y Rubio, 2021).

The BH1750 sensor presents itself as a balanced choice for greenhouse brightness measurement. Although it is not the cheapest sensor (LDR $1.25) or the widest range (1-65535 lx), it offers an I2C digital output that facilitates integration with microcontrollers and an accuracy of 1 lx, all at an affordable cost of $2.50. This combination of features makes it an efficient alternative for controlling lighting and optimizing plant growth (García et al., 2014).

The MH-Z19B sensor stands out as the superior choice for $CO_2$ monitoring in smart greenhouses despite its high cost of $25. The MH-Z19B provides a digital UART output, facilitating integration with IoT systems, and covers a wide range of 0-5000 ppm, ideal for greenhouse environments. Its accuracy of ±50 ppm + 5% is critical for precise control of $CO_2$ levels, an essential factor in optimizing plant growth (García et al., 2014).

The capacitive soil sensor is slightly more expensive ($3.5 versus $1.50 for the FC-28), but offers advantages in terms of durability and accuracy (Jiménez y Quishpe, 2020).

**Controller**

The choice of controller depends on factors such as budget, connectivity needs, required performance, and safety requirements (Cevallos y Rubio, 2021). Table 2 show some features about different controllers.

The ESP32 controller is the best choice for intelligent greenhouse monitoring and control systems due to its combination of features and low cost. Priced at $10, it offers integrated WiFi and Bluetooth connectivity, making it easy to communicate with IoT devices. In addition, it has 34 GPIO pins, surpassing the Arduino (20 pins) and ESP8266 (17 pins), allowing simultaneous connection of multiple sensors and actuators. Compared to alternatives such as Raspberry Pi ($300) or PLC ($500), the ESP32 is more economical, consumes less power (3.3V) and is ideal for applications that require a balance between functionality and economic efficiency (ESP32, 2024).

**Table 2.** Controllers

| Controller | Description | Pines | V Fun | Precio |
|---|---|---|---|---|
| Arduino | Additional modules | 14 digital, 6 analog | 5V | $20 |
| ESP8266 | Built-in WiFi | 17 | 3.3V | $5 |
| ESP32 | WiFi and Bluetooth | 34 | 3.3V | $10 |
| Raspberry Pi | Computer | 40 GPIO | 5V | $300 |
| PLC | LAN connection | 8 digital and S-6 digital | 24V | $500 |

**Fuente:** ALLDATASHEET, 2025

**IoT communication system**

In the field of microcontroller development, IoT communication systems are essential for data transfer between devices, as shown in Table 3.

**Table 3.** IoT Communication

| Protocol | Range | Power Consumption | Typical Applications |
|---|---|---|---|
| Wi-Fi | 50 m | High | Home networks, offices |
| Bluetooth | 10 m | Low | Headphones, speakers, peripherals |
| Zigbee | 100 m | Low | Home automation, industrial control |
| LoRaWAN | 3 km | Very low | Long-range IoT, smart cities |

**Fuente:** ALLDATASHEET, 2025

In the world of wireless communications, there are several technologies designed to meet different needs. For example, Wi-Fi is widely known for its high speed and is commonly used in homes and offices. Bluetooth, on the other hand, specializes in short-range, low-power connections. For applications requiring long-distance communications, LoRaWAN stands out in the IoT field thanks to its energy efficiency. Zigbee also comes into play, with its mesh structure and low power consumption, making it suitable for various applications (Figueredo y Velasco, 2018).

Table 4 details the actuators selected for the smart greenhouse system, including components for ventilation, heating, misting, irrigation and lighting. Each entry specifies the product, the store where it was purchased (Amazon), its operating voltage (120V), power in watts (W) and cost in dollars ($), as well as a link to facilitate the purchase. It is observed that the heating system requires the greatest power (1500W), while the pump for the hydropneumatic irrigation system has a considerable consumption (380W).

**Table 4.** Actuators

| **Components** | **Product** | **Shop** | **(V)** | **(W)** | **$** |
|---|---|---|---|---|---|
| Ventilation | 12 inch Exhaust Fan | KEN BROWN | 120 | 63 | 64 |
| Heating | 1500W Electric Heater | VEVOR | 120 | 1500 | 33 |
| Nebulization | 59ft nebulizer | HOMENOTE | | | 35 |
| Irrigation | 50 m hose, 50 dropper. | ABAKUKU | | | 28 |
| Irrigation | 1/4 Inch Solenoid Valve | U.S. Solid | 120 | 14 | 19 |
| Irrigation | Hydropneumatic System Jet Pump 0.5 Hp | LEO | 120 | 380 | 169 |
| Light | IP44 LED Grow Lights | DANSHINRO | 120 | 300 | 80 |

**Fuente:** ALLDATASHEET, 2025

## Analysis of Results

### Irrigation systems

According to Table 5, the drip irrigation system is the most adaptable to soil moisture in an automated system. Its high-water use efficiency (minimal losses) and its ability to apply water in a localized manner allow the amount of water delivered to be precisely adjusted in response to soil moisture sensor readings. Although its initial cost and maintenance are high, the ability to optimize water use makes it a sustainable and effective option for irrigation management in smart greenhouses.

**Table 5.** Characteristics of irrigation types

| Feature | Spray | Nebulization | Drip |
|---|---|---|---|
| Application | Rain form | Very small drops | Continuous drops |
| Wate rtransportation | Pressure pipes | Low pressure pipes | Pipe network |
| Water use | High | Moderate | Low |
| Pressure required | 2,5 - 4,5 kg/cm² | 1,6 kg/cm² | 1,2 kg/cm² |
| Coverage area | Wide | Moderate (3-4 meters) | Localized |
| Water efficiency | Low | Moderate (low consumption) | High (minimal losses) |
| Maintenance | Moderate | Moderate | High |
| Initial cost | Moderate | Moderate | High |
| Adaptability | Low | High for fruit trees and nurseries | High |

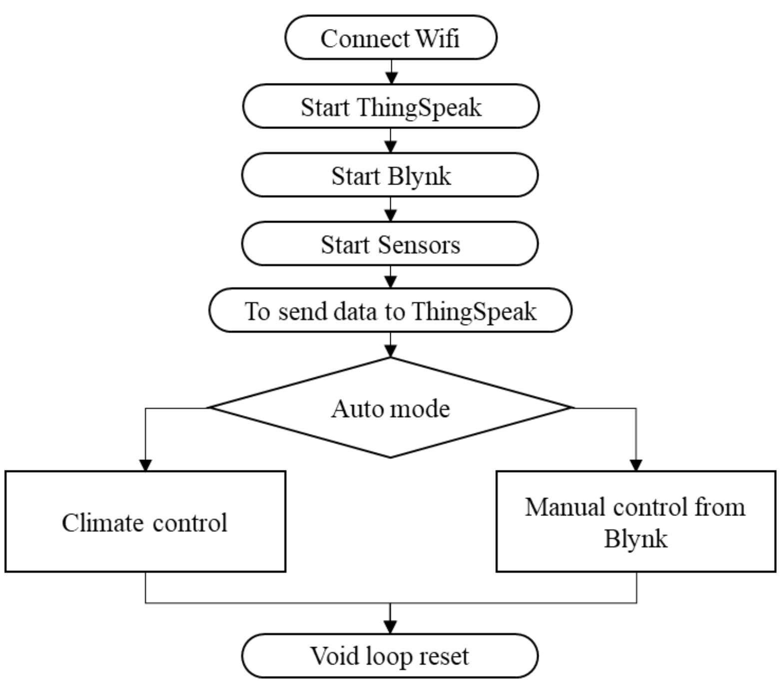
**Fuente:** MANUAL DE RIEGO PARA AGRICULTORES MÓDULO 1 POR R. FERNÁNDEZ GÓMEZ, M. MILLA Y R. AVILA ALABARCES.

**Real-time monitoring using IoT technology**

**Programming Analysis**

The flowchart in Figure 4 describes the process of the intelligent automated monitoring and control system for greenhouses. Initially, the program establishes the WiFi connection and sets up communication with ThingSpeak to send data, followed by authentication with Blynk and initialization of the sensors. Collected data, including temperature, humidity, ambient light, soil moisture and CO2 levels, are sent to ThingSpeak for remote monitoring. Depending on the mode selected, the system operates in automatic control by adjusting the actuators based on the sensor values and hysteresis levels set. Alternatively, in manual mode from Blynk, the user can directly intervene in the climate and irrigation parameters. Finally, the program restarts the cycle in the main loop to ensure continuous operation.

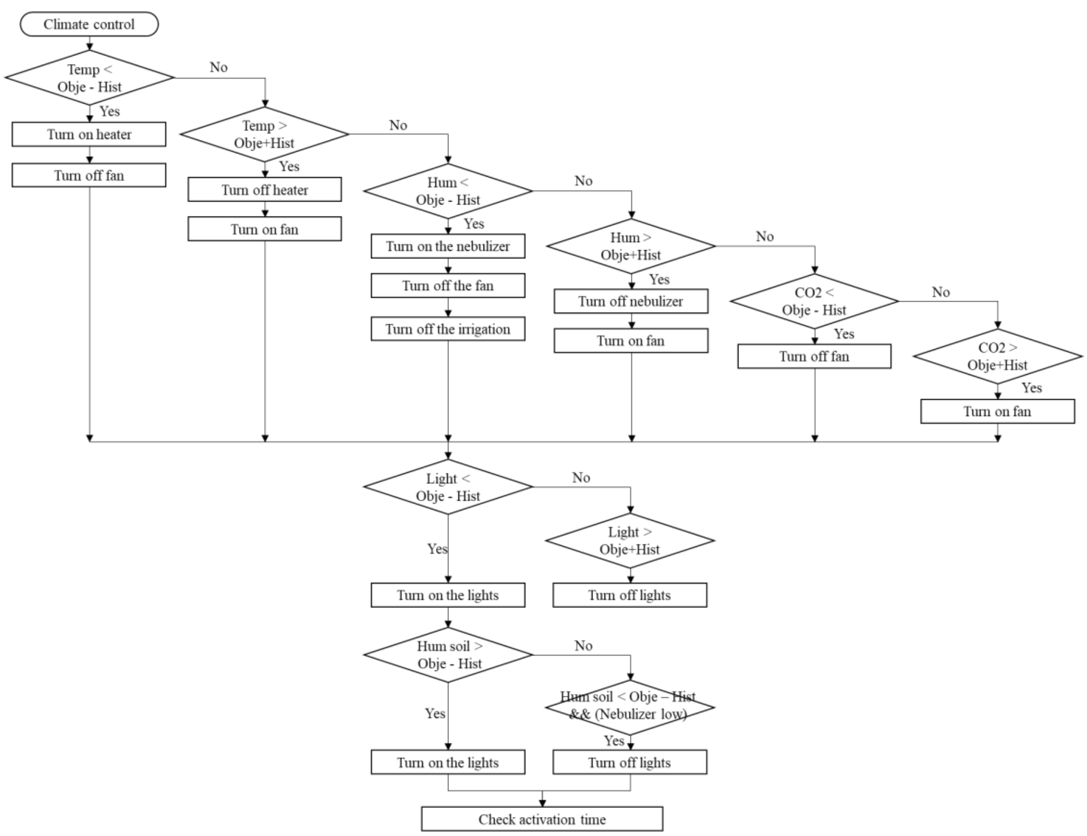
**Figure 4.** Process of the intelligent automated monitoring and control system for greenhouses




**Fuente:** Autores, 2025

Figure 5 shows the flowchart of the automated greenhouse climate control system, based on hysteresis values set for each environmental parameter. The process starts with the evaluation of the temperature: if it is lower than the target minus the hysteresis, the heater is activated; if it exceeds the target plus the hysteresis, the heater is turned off and the fan is turned on. Subsequently, the relative humidity is analyzed; if it is below the set range, the nebulizer is activated, and if it exceeds the limit, the nebulizer is turned off and the fan is adjusted. The CO2 level is also monitored: if it is below the threshold, the fan is turned off, and if it exceeds the limit, the fan is activated. In addition, light and soil moisture are regulated; lights are switched on or off according to the detected light levels, while irrigation is adjusted depending on soil moisture and fogger conditions.

**Figure 5.** Automated greenhouse climate control system

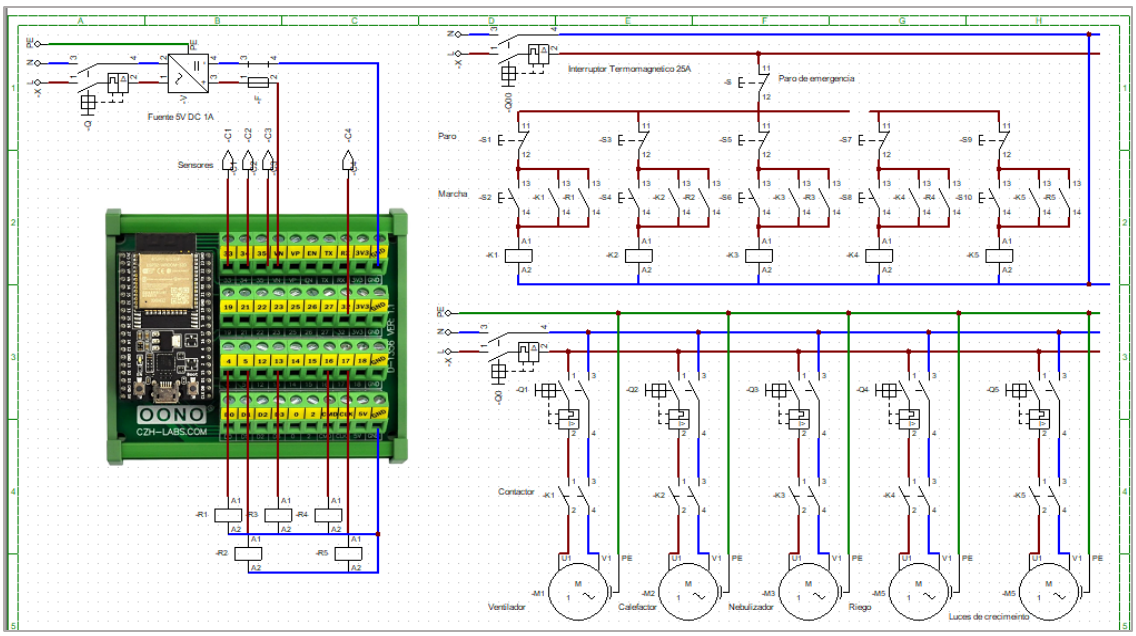



**Fuente:** Autores, 2025

## Connection scheme

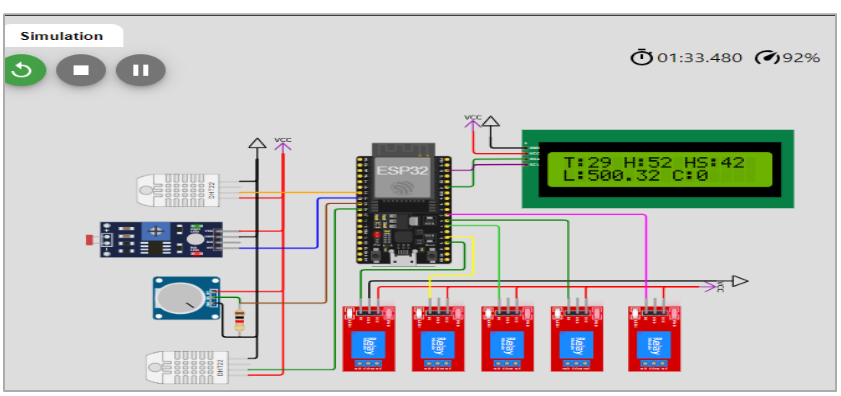
Contingency equipment was considered, as shown in Figure 6 and Figure 7, as an alternative in case the control cannot be done through the internet. This setting is an additional increment in the project of designing an intelligent system for a greenhouse.

**Figure 6.** Power system connection diagram




**Fuente:** Autores, 2025

**Figure 7.** ESP32 and sensors connection diagram

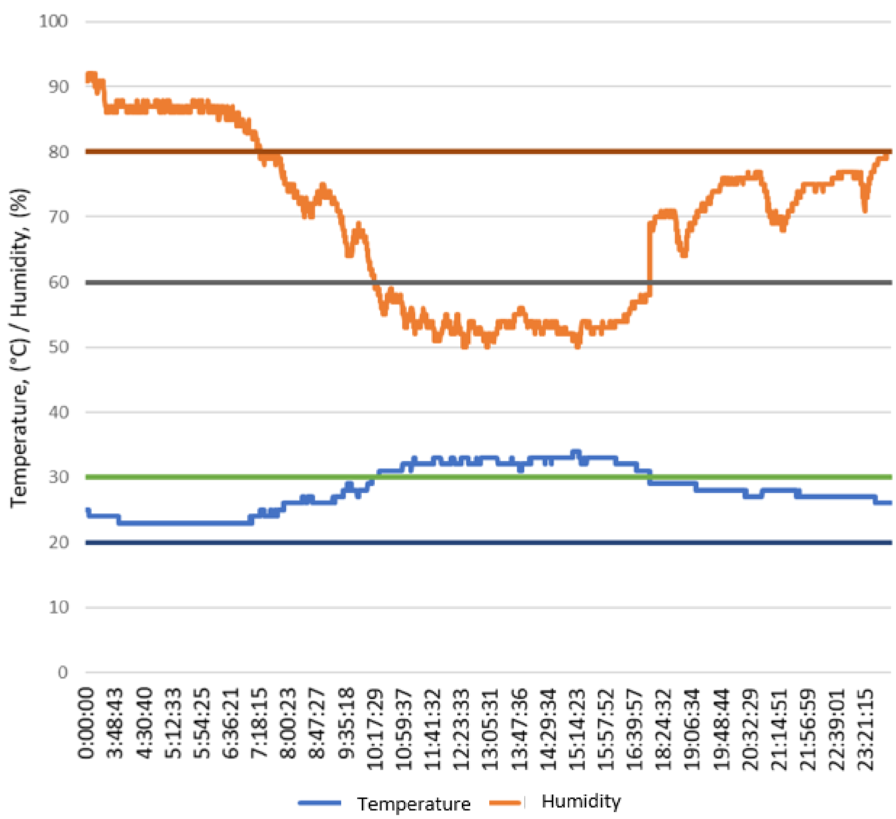



**Fuente:** Autores, 2025

**Measurements**

Figure 8 shows the behavior of temperature and relative humidity over a 24-hour period in the greenhouse. A setpoint of 25 ± 5°C for temperature and 70 ± 10 % for relative humidity was set. The temperature, represented by the blue line, is maintained within a stable range between 20°C and 30°C, with slight variations reflecting the natural cycles of day and night. Fan operation is used in the system to stabilize the observed variation.On the other hand, the relative humidity, indicated by the orange line, exhibits more pronounced fluctuations, starting near 90% in the early hours of the day and progressively decreasing to reach minimum values near 50% in the central hours, which causes the activation of the humidifiers to correct this decrease and reestablish the desired levels.

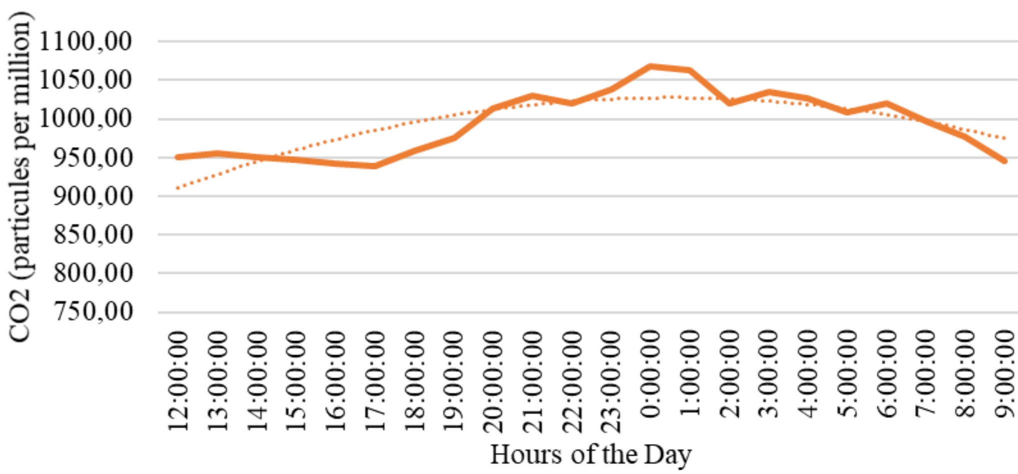
**Figure 8.** Behavior of temperature and relative humidity




**Fuente:** Autores, 2025

Figure 9 shows the behavior of $CO_2$ concentrations in the greenhouse during a 24-hour period, expressed in particles per million (ppm). A gradual increase is observed from 12:00 noon until reaching a maximum peak close to 1,100 ppm around 22:00. Subsequently, concentrations begin to decrease progressively, reaching minimum values near 950 ppm at the end of the period. This pattern reflects the accumulation of $CO_2$ during the hours of lower ventilation and its decrease with air renewal.

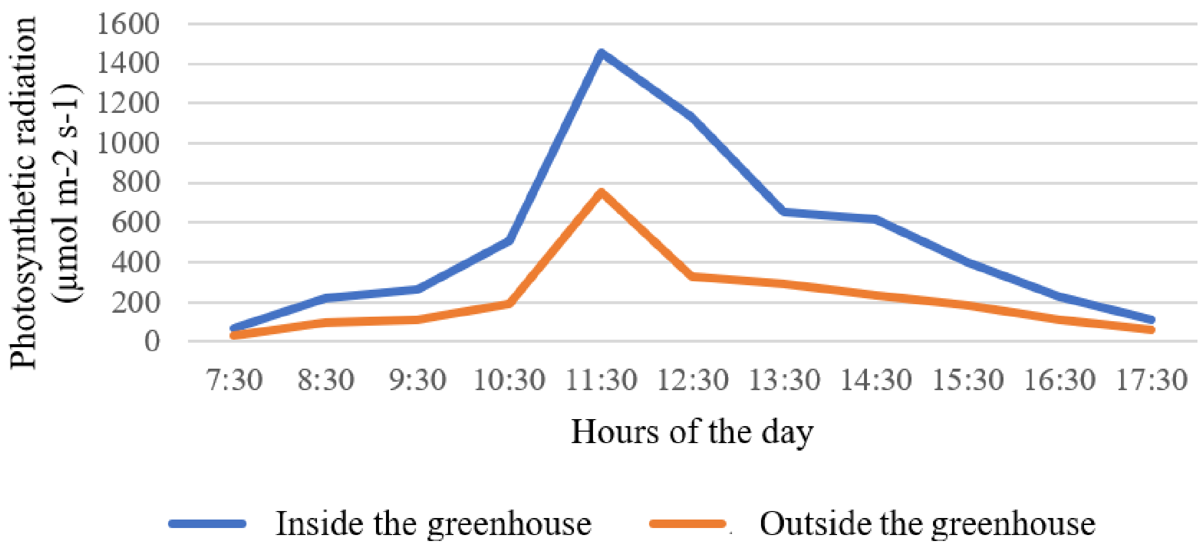
**Figure 9.** $CO_2$ measurements




**Fuente:** Autores, 2025

**Figure 10** shows that photosynthetic radiation outside the greenhouse (blue line) reaches a maximum peak close to 1,500 µmol/m²/s around 12:30, while inside the greenhouse (orange line), the maximum value is significantly lower, reaching approximately 600 µmol/m²/s at the same time. This behavior reflects the attenuation of radiation caused by the structural and covering materials of the greenhouse, which reduces the light intensity available to the plants.

**Figure 10.** Measurement of photosynthetic radiation




**Fuente:** Autores, 2025

**Table 6.** Investment cost

| Category | Subcategory | Quantity | Unit Price ($) | Total Price ($) |
|---|---|---|---|---|
| | Router | 1 | 20 | 20 |
| | 5V relay module - 5 channels | 1 | 5 | 5 |
| | ESP32 rail support | 1 | 22 | 22 |
| Hardware | ESP32 | 1 | 9 | 9 |
| | DHT22 sensor, BH1750 Sensor | 1 | 6.5 | 9 |
| | CO2 sensor | 1 | 25 | 25 |
| | Capacitive sensor | 1 | 2 | 2 |

| | | | | |
|---|---|---|---|---|
| Actuators | Electrovalve | 2 | 19 | 38 |
| | Led grow light | 1 | 80 | 80 |
| | Air extractor | 1 | 64 | 64 |
| | Dropper and Hose Kit | 3 | 28 | 84 |
| | Heat | 1 | 33 | 33 |
| | Nebulization Kit | 1 | 35 | 35 |
| Cable | Cable 3 x 18 AWG | 8 | 1.2 | 9.6 |
| | Cable 3 x 14 AWG | 40 | 1.5 | 60 |
| | Cable 3 x 12 AWG | 10 | 2.15 | 21.5 |
| | Cable 3 x 10 AWG | 10 | 3.3 | 33 |
| Protection | 1p 2A thermal magnetic switch | 4 | 3.5 | 14 |
| | 1p 4A thermal magnetic switch | 1 | 3.5 | 3.5 |
| | 1p 6A thermal magnetic switch | 1 | 3.5 | 3.5 |
| | 1p 16A thermal magnetic switch | 1 | 3 | 3 |
| | 1p 25A thermal magnetic switch | 1 | 3.25 | 3.25 |
| | DC fuses 2A, 0.5A | 1 | 1 | 2 |
| Control Equipment | AC-DC source | 1 | 13 | 13 |
| | 40x30x20 cm board | 1 | 60 | 60 |
| | 30x30 mm x 2m trunking | 1 | 7.28 | 7.28 |
| | Emergency stop | 1 | 5 | 5 |
| | 12 AWG rail terminal block | 5 | 7 | 35 |
| | Bornera de riel 12 AWG | 22 | 0.3 | 6.6 |
| | 3p AC3 9A contactors | 5 | 10 | 50 |
| | 35 mm DIN rail | 2 | 12 | 24 |

| | |
|---|---|
| Total | 780.23 |

**Fuente:** Autor, 2025

**Economic feasibility of the intelligent monitoring system**

**Economic analysis using alternative technology**

The economic feasibility of different automation platforms -ESP32, Arduino, LOGO V8 and PLC S7-1200- was analyzed for implementation in control projects in greenhouses and urban orchards, ESP32 stands out for its low cost and high performance in IoT applications. It facilitates the development of intelligent systems for automation and environmental monitoring in greenhouses, the price range for ESP32 and Arduino boards is $5 to $10. On the other hand, Arduino, another low-cost option, is ideal for real-time monitoring and control of climate conditions in greenhouses and home gardens.

The LOGO V8 controller, in combination with the CMR2020 module, offers an economical and reliable solution for automated irrigation systems, enabling irrigation control. Prices for the LOGO CMR2020 module and LOGO V8 controller range from $100 to $500. Finally, the S7-1200 PLC, although more advanced and expensive, is designed for large-scale industrial projects; the price range for the S7-1200 PLC is $500 to $1000.

**Design investment**

The project has a total cost of $780.23 considering contingency equipment, as shown in Table 6, with most of the budget going to the actuators ($329) and control equipment ($201). The most expensive components include the LED grow light, dripper and hose kit, and control board. Hardware accounts for a smaller portion of the total cost ($40).

**Investment recovery analysis**

The implementation of greenhouse technology generates an increase in production, in a study conducted by the Universidad Autónoma Agraria Antonio Narro, it was determined that the use of basic technology generates an increase in production from 120 Tn/ha to 240 Tn/ha, this result is used to estimate the improvement in production from 120 Tn/ha to 200 Tn/ha for the system, as shown in Table 7, which represents an increase of 66.7%. The initial investment is $780.23, with a low annual maintenance cost of $40. The energy consumption is 10 kWh/day, resulting in a monthly cost of $28.

**Profit analysis**

The 66.6% payback model Table 8 stands out for its ability to generate a return on investment quickly and efficiently. Starting in the second quarter, this model achieves a positive payback of $175.90, thanks to higher revenues of $423.29 per quarter. On the other hand, the 30% payback model (Table 9) presents a much slower payback process. It does not achieve a positive payback until the fourth quarter, with a profit of $200.43 in that period. With significantly lower revenues of $190.48 per quarter, this model prolongs the time needed to recover the investment, resulting in a delayed, though eventually profitable, return.

**Table 7.** Operating costs

| Description | Unit | Estimated Value |
|---|---|---|
| Estimated consumption for 8 hours a day | kWh/día | 10 |
| Monthly energy cost | $/mes | 28 |
| Labor all week | $/mes | 420 |
| Labor 4 days a week | $/mes | 240 |
| Initial investment | $ | 780.23 |
| Annual maintenance | $ | 40 |
| Greenhouse production without technology | Tn/ha | 120 |
| Greenhouse production with technology | Tn/ha | 200 |

| | | |
|---|---|---|
| UTEQ greenhouse area (study) | m² | 120 |
| Production without technology (study) | lb/m² | 1.44 |
| Production with technology (study) | lb/m² | 2.4 |
| Production price in collection centers | $/lb | 0.2 |

**Fuente:** Autor, 2025

**Table 8.** Investment recovery (66.6%)

| Quarterly | Profit ($) | Maintenance ($) | Electricity bill ($) | Labor savings ($) | Return ($) |
|---|---|---|---|---|---|
| 1 | 423.29 | 13.33 | 112 | 180 | -302.04 |
| 2 | 423.29 | 13.33 | 112 | 180 | 175.90 |

**Fuente:** Autor, 2025

**Table 9.** Investment recovery (30%)

| Quarterly | Profit ($) | Maintenance ($) | Electricity bill ($) | Labor savings ($) | Return ($) |
|---|---|---|---|---|---|
| 1 | 190.48 | 13.33 | 112 | 180 | -434.85 |
| 2 | 190.48 | 13.33 | 112 | 180 | -289.7 |
| 3 | 190.48 | 13.33 | 112 | 180 | -44.43 |
| 4 | 190.48 | 13.33 | 112 | 180 | 200.43 |

**Fuente:** Autor, 2025

## Conclusions

The design of the real-time monitoring system using IoT technology, focusing on environmental parameters such as temperature, humidity, lighting and carbon dioxide concentration, proved to be effective. The Blynk and ThingSpeak platforms provided a robust basis for environmental management in greenhouses, allowing efficient data collection and analysis.

The drip irrigation system proved to be the most efficient in adapting to changing soil moisture and climate conditions in greenhouses. This method minimizes evaporation and runoff losses, and its low-pressure operation significantly reduces energy consumption.

The economic analysis revealed that the developed climate control system is highly profitable. With a 66.6% increase in production, the system manages to recover the investment in half the expected time, generating a positive balance of $175.90 in the second quarter. This shows that the technology used, such as the ESP32, offers a low-cost, high-performance solution, especially suitable for small farmers.

The implementation of technology in greenhouses showed a significant increase in crop production, offsetting the initial and operating costs. This makes the system an attractive investment to improve agricultural productivity, especially in intensive production environments.

The developed system demonstrated competitive advantages compared to other smart controllers on the market, standing out for its cost-effectiveness, versatility and ease of maintenance. Its price of $50 for the electronic part makes it significantly more accessible than other commercial options.

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