

# Sensing Parameters Related to the Cultivation Environment and Hydroponic Solution for Automation Purposes

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## ABSTRACT

**Objective:** Automation in various industrial sectors has proven to be a relevant alternative, enhancing speed and reliability of activities. It reduces task execution time, ensures greater operational efficiency, minimizes operator interventions, cuts production costs, and optimizes the production chain. This work aims to present an engineering solution regarding the sensing of environmental parameters in a hydroponic greenhouse for automation and real-time monitoring through a Human-Machine Interface developed in collaboration with another research project.

**Design/methodology/approach:** An ATmega 2560 microcontroller on the Arduino Mega 2560 platform, along with sensors for flow, temperature, humidity, luminosity, solution level, and flow presence, served as climate and greenhouse system readers. The open-source ScadaBR software was employed as the supervisory system for online monitoring.

**Results:** The developed system enabled tracking the state of the hydroponic system through a web interface with graphs illustrating changes in system parameters over time.

**Findings/conclusions:** The implementation of an automated monitoring and control system in a hydroponic greenhouse demonstrated the potential to improve operational efficiency, data accessibility, and crop management. By integrating low-cost sensors, open-source hardware, and ScadaBR supervisory software, it was possible to monitor temperature, humidity, luminosity, flow rate, and solution level in real time, with responsive actuators triggered when thresholds were exceeded.

**Keywords:** Real-time simulation, Transmitters, Distributed control, Control systems.

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## INTRODUCTION

The automation of production processes has increased the safety and agility of activities in different industrial sectors and can reduce the time it takes to carry out a given task, thus ensuring operational efficiency, and even reducing production costs. In automation, a central processing unit with peripherals, such as a personal computer, programmable logic controller (PLC) or even a microcontroller, is programmed to read sensors and act on the process, when necessary, to stabilize it. In the agricultural field, the automation

of horticultural crops has generated positive advances, which is why it is becoming increasingly widespread in small, medium, and large-scale crops, Barauskas *et al.* (2022); Naveena *et al.* (2024). Linked to this, there is a continuous search by producers for advances in technologies that allow production to be automated, thus generating high quality products with reduced costs and greater profitability, reducing time, and providing freedom to the producer, Untoro and Hidayah (2022).

Automation not only reduces the risk of losing the crop but also makes it possible to improve the quality of products by providing optimum production conditions, allowing autonomy in cultivation and, consequently, human labor to be directed towards activities that require greater intellectual dedication. Hydroponic cultivation has been shown to be an alternative for producers who want to produce products without the application of chemical pesticides, with high added value, close to urban centers and with restricted surface area for cultivation. Other reasons that have encouraged this type of cultivation are the difficulties encountered in conventional production due to various factors, including temperature control, humidity, wind, soil fertility and pest control, making it necessary to implement more advanced technological resources, such as automation, to assist in daily activities, Alselek *et al.* (2022); Untoro and Hidayah (2022).

Maintaining a hydroponic system usually requires the recurring presence of the operator to keep the system in good working order. One way of reducing the presence of the operator is to monitor the operation of the hydroponics system and enabling him to carry out other activities while keeping an eye on the operation of the greenhouse is to monitor it online. Hydroponics is a technique for growing plants without soil, in a water environment, where the roots receive a balanced nutrient solution made up of water and the nutrients needed for the plant to develop properly, Rouphael and Colla (2019). It should also be noted that this is a new technique in Brazil, and the trend is for it to be used more in places where the climate is unstable, hindering agricultural development. In this context, automation is important for reducing losses by controlling multiple variables in crop shelters, Lopes *et al.* (2014); Kurniasari *et al.* (2025).

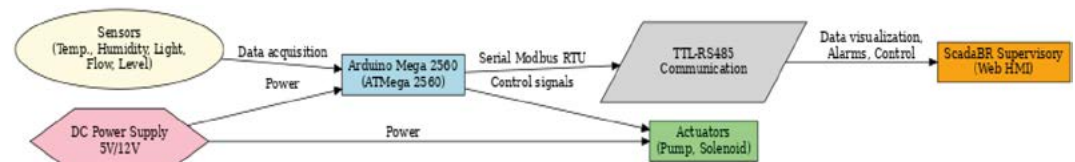
Despite these advances, most studies in hydroponic automation have focused on specific parameters such as pH and electrical conductivity (EC), often using high-cost commercial systems, Domingues *et al.* (2012); Rouphael & Colla (2019); Untoro and Hidayah (2022). Few works address the integration of multiple low-cost sensors into an open-source supervisory system, especially one like ScadaBR, which enables remote, web-based monitoring with accessibility for small and medium-sized producers. This study contributes by implementing and evaluating such a system under real greenhouse conditions, highlighting its scalability, affordability, and potential for democratizing access to automation technologies in protected cultivation, Kurniasari *et al.* (2025). Unlike most studies that focus only on pH and EC monitoring, this work integrates multiple low-cost sensors into an open-source supervisory platform (ScadaBR), enabling real-time web-based monitoring accessible to small and medium-scale producers. Therefore, the objective of this study was to develop and evaluate a low-cost automation system for hydroponic greenhouses, integrating multiple sensors with the open-source ScadaBR platform. Based on this, it is hypothesized that the integration of low-cost

sensors into an open-source supervisory platform (Arduino Mega 2560 + ScadaBR) can ensure reliable real-time monitoring of hydroponic cultivation parameters (temperature, humidity, luminosity, flow rate, and solution level), providing performance comparable to commercial high-cost systems, while maintaining affordability and accessibility for small and medium-sized producers. This combination of Arduino Mega 2560 and ScadaBR represents a unique contribution, since most previous works relied on commercial controllers or simulations, Penjor *et al.* (2022). By using a fully open-source and low-cost platform, the present study expands automation accessibility for small and medium-scale farmers, democratizing technologies that are often restricted to large-scale production. This practical validation under tropical greenhouse conditions also distinguishes the present work from most studies that remain at a simulation or laboratory stage.

## MATERIALS AND METHODS

Figure 1 shows an overview of the applied approach, such as the Arduino Mega2560 development platform and the sensors, to monitor the operation of the greenhouse as well as the actuators, which act to stabilize some variables of the process, the human-computer interface developed with the software (ScadaBR), responsible for developing all the online interfaces used in this work, and the procedures used above each stage. To validate this hypothesis, the proposed system was implemented and tested under real hydroponic greenhouse conditions, monitoring critical environmental and solution parameters.

The project was carried out in a hydroponic greenhouse at the Federal University of Recôncavo da Bahia-UFRB, located in the Trio-Elétrico residence on the Cruz das Almas Campus, and data collection for system evaluation took place between June and August 2019. The municipality is in the Recôncavo Baiano physiographic region, with geographical coordinates of 12° 40' 19" south latitude, 39° 06' 23" west longitude from Greenwich and an average altitude of 220 m. The local climate is subsumed, with an average temperature of 24.1 °C and average rainfall of 1170 mm; Almeida & Ferreira (2022); Fabiano and Borges-Filho (2024). The greenhouse is 48 m in size 2, with a 4 m high roof and 3 m high sides with two roofs. It is covered by a transparent tarpaulin and a 50% screen on all sides of the greenhouse. Inside, there are three growing benches: The first growing level was 1m high at the head, 6m long with a 10% slope at the end and containing 7 70 mm tubes spaced 20 cm apart; the second was 1.70 m high at the head and had a 10% slope at the end with 5 0.70 m × 6 m tubes spaced 30

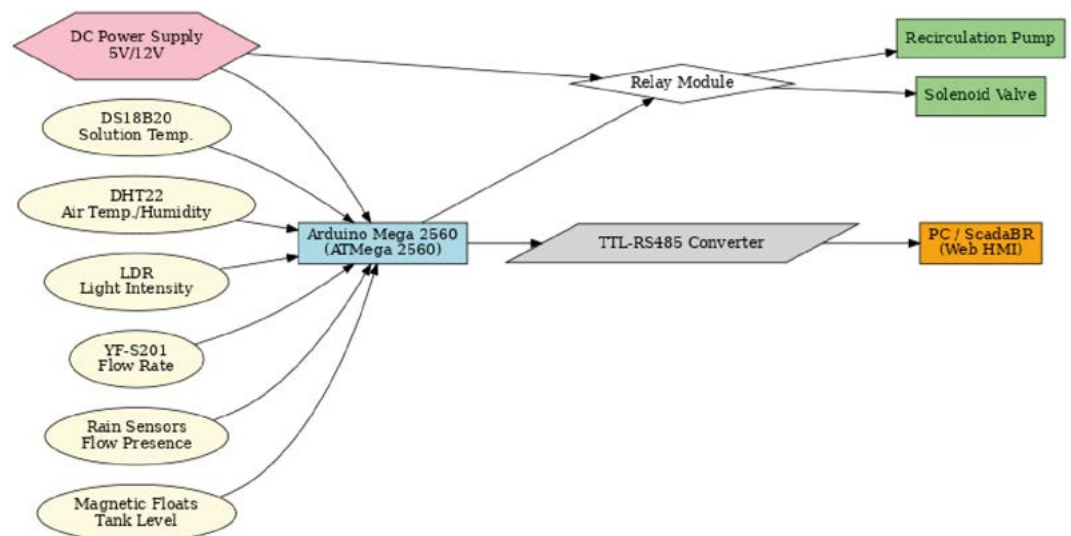


**Figure 1.** Workflow diagram of the hydroponic monitoring and control system, showing data acquisition from sensors, processing by the Arduino Mega 2560, communication with the ScadaBR supervisory system, and actuation through pump and solenoid.

cm apart. The two levels have the capacity to grow 480 coriander plants. For system automation, the Arduino Mega 2560 platform was adopted, based on the ATmega2560 microcontroller, due to its versatility and multiple input/output ports, which make it suitable for connecting several sensors and actuators simultaneously. The integration between sensors, actuators, the microcontroller, and the supervisory interface is illustrated, Soetedjo and Hendriarianti (2023).

To automate the project, hardware had to be built to monitor the meteorological parameters of the greenhouse's internal environment, such as temperature, humidity, and light. As for the nutrient solution used in hydroponic cultivation, the temperature, reservoir level, flow in the cultivation channels and a solenoid actuator to add water to the reservoir when the level is low were evaluated. For online monitoring, a partnership was made with the work of, where a SCADABR supervisory system was used in his work, which aimed to develop a low-cost supervisory system. All the greenhouse's parameters were monitored using the operation and control system developed in ScadaBR. In addition, it gives the user daily access to all the data recorded and the option of creating alarms if something unexpected (out of the ordinary) happens in the system. It also allows the operator to access it from any electronic device such as a desktop, notebook, tablet, or smartphone, if it has internet access, Almeida and Ferreira (2022); Sulaiman *et al.* (2025).

In order to be able to access the monitoring, it was necessary to keep a fixed computer in the hydroponic greenhouse, connected to the network 24 hours a day, so that it was possible to receive the data from the TTL-RS485 connected to the Arduino board inside the hydroponic greenhouse and transmit it via cable to a USB-RS485 serial converter connected to the computer, through which the operator had access to the data and graphs, which could also be accessed from another location via a telephone with the address and password pre-defined in the system, Almeida and Ferreira (2022); Soetedjo and Hendriarianti (2023).



**Figure 2.** Simplified scheme showing the interconnection between sensors, actuators, and the Arduino Mega 2560 microcontroller, with RS485 communication to the ScadaBR supervisory software.

### Sensors for data Collection

Determining which sensors would be used in the system was only possible after studying how hydroponic cultivation works and the main parts needed for operation and monitoring, Resh (2001). After this initial study, a bench with two cultivation levels was separated inside the greenhouse to carry out the project with the following components: two 90° side water level floats magnetic switch type, a DS18B20 temperature sensor, a solenoid valve for water model A147B coil voltage 127v (NC- normally closed), flow sensor water flow 1/2" model Yf-s201-30l min<sup>-1</sup>, two rain sensors (detector) used as flow sensors, a DHT22 (humidity and temperature), a 5mm photoresistor LDR, a 4-channel 5v relay module, a TTL - RS485, USB- RS485 module, an Arduino Mega 2560 and two 5V DC supplies.

### Recirculation tank water level sensor

The sensor installed to monitor the water level is a horizontal magnetic type with a 90° float. This mini float is an instrument used to monitor the water level in a box or similar. The sensor does not report the amount of water in analog form, but whether water is present in a certain position. It can be used in conjunction with another float, which, with the help of a relay, will trigger a solenoid when the water level is lower than the second

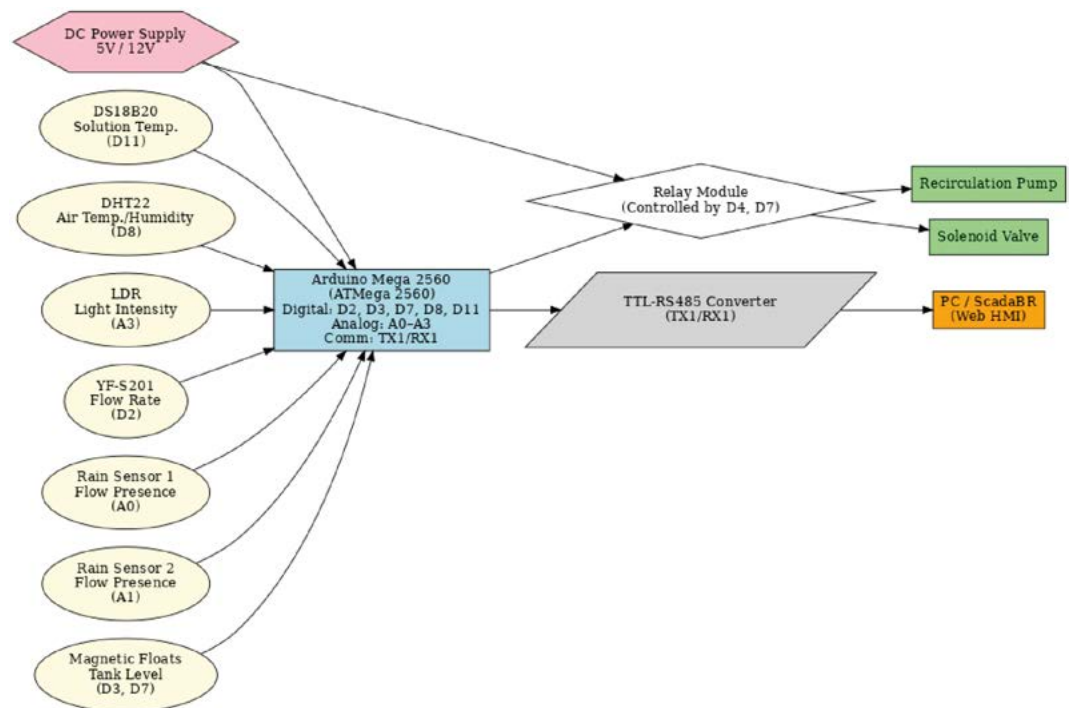
**Table 1.** Sensors and actuators are used in the hydroponic monitoring and control system.

Device	Model/Type	Measurement range	Accuracy	Function in the system
Water level float switch	Magnetic, 90° side type	Presence/absence (binary)	–	Detects high/low nutrient solution levels
Temperature sensor	DS18B20 (digital)	–55 to 125 °C	±0.5 °C	Monitors nutrient solution temperature
Humidity & temp. sensor	DHT22 (digital)	–40 to 125 °C; 0-100% RH	±0.5 °C; ±2-5 %RH	Monitors ambient temperature and humidity
Flow sensor	YF-S201 (Hall effect)	1-30 L/min	±10%	Measures nutrient solution flow rate
Flow presence sensors	Rain sensors (detectors)	Presence/absence (binary)	–	Detects nutrient solutions at each cultivation level
Light sensor	LDR 5 mm photoresistor	Relative light intensity	–	Measures luminosity inside the greenhouse
Solenoid valve	A147B, 127 V (NC)	0.2-8 kgf/cm <sup>2</sup> (operating)	–	Automatic refilling of the nutrient tank
Relay module	4-Channel, 5 V	Up to 10 A load	–	Controls solenoid valve and pump
Real-time clock (RTC)	DS1302	Timekeeping functions	–	Provides time/date for logging and scheduling

Authorial

float, as was done in the project, Sulaiman *et al.* (2025). A 220 Ohm resistor was used in the graduated neutral density filter (GND) terminal and float 1 was connected to digital port 03 and float 2 to port 07. The DS18B20 digital sensor was used to monitor nutrient solution temperature (range  $-55$  to  $125$  °C, accuracy  $\pm 0.5$  °C). Flow was measured with a YF-S201 Hall-effect sensor (range 1-30 L/min,  $\pm 10\%$  accuracy).

The sensor has 3 wires for connection to the system: red (vcc), black (GND) and yellow (data). An important detail is the 4.7K pull-up resistor between VCC and the data wire. Without it, the sensor will not be detected by the program, and it is connected to digital port 11. The DS18B20 digital sensor was used to monitor nutrient solution temperature (range  $-55$  to  $125$  °C, accuracy  $\pm 0.5$  °C). A normally closed solenoid valve ( $127$  V,  $0.2$ - $8$  kgf/cm<sup>2</sup>) was used for automatic refilling of the nutrient tank. Flow rate was measured with a YF-S201 Hall-effect sensor (range 1-30 L/min, accuracy  $\pm 10\%$ ). Rain sensors were repurposed as flow detectors to identify nutrient solution presence at each cultivation level. Ambient temperature and humidity were monitored with a DHT22 sensor (range  $-40$  to  $125$  °C,  $\pm 0.5$  °C; 0-100% RH,  $\pm 2$ -5%), Sulaiman *et al.* (2025). Light intensity was measured using a 5 mm LDR photoresistor, with resistance inversely proportional to incident light. A 4-channel 5 V relay module was used to control the solenoid and pump, supporting loads up to 10 A and electrically isolating the Arduino from actuators. Communication between Arduino and ScadaBR was established using a TTL to RS-485 converter with Modbus RTU protocol, ensuring reliable long-distance



**Figure 3.** Expanded simplified electrical/signal scheme showing the interconnection between sensors, actuators, Arduino Mega 2560 microcontroller (with main pins), and RS485 communication to the ScadaBR supervisory software.

data transmission. A DS1302 real-time clock (RTC) provided timekeeping functions (hours, date, leap year adjustment) for data logging and scheduling, Kushawaha (2024); Austria *et al.* (2023).

### Firmware Development

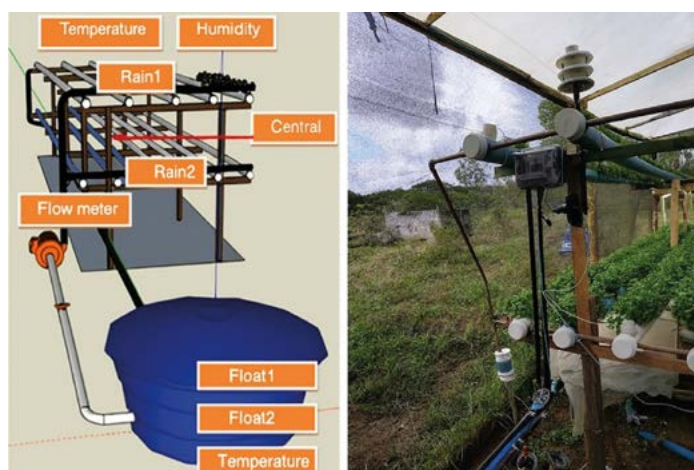
After assembling the hardware, an open-source code was developed within Arduino's own Integrated Development Environment (IDE). The environment allows you to group together a set of step-by-step information about what you want to do using a computer language, and then these programs, also known as sketches, are downloaded via a Universal Serial Bus (USB) cable to the microcontroller (Arduino Mega2560), which is responsible for reading the electrical pulses coming from the sensors, transforming them into a high-level programming language (C and C++), processing the computer logic and transforming it into graphic data that can be viewed on the screen by the ScadaBR software via the RS-485 module.

### Development and Interconnection of the System to Sensors and Actuators

The microcontroller programming stage was completed, containing the implementation of all the sensors and actuators already mentioned, Austria *et al.* (2023). The list with the "Pin out" and the positioning of each sensor and actuator has been identified. In the following sections, the execution (hardware) of each component will be reported step by step, as illustrated by the architecture.

### Sensor Installation

During the installation of the sensor modules, the procedures described in this section of the text were of great value, because as these sensors are easy to acquire and low cost, it is necessary to take certain precautions with them. In this study, mechanical protection was created using 75mm PVC pipes to prevent humidity, rain, and direct contact with the sun's rays from damaging the sensors.

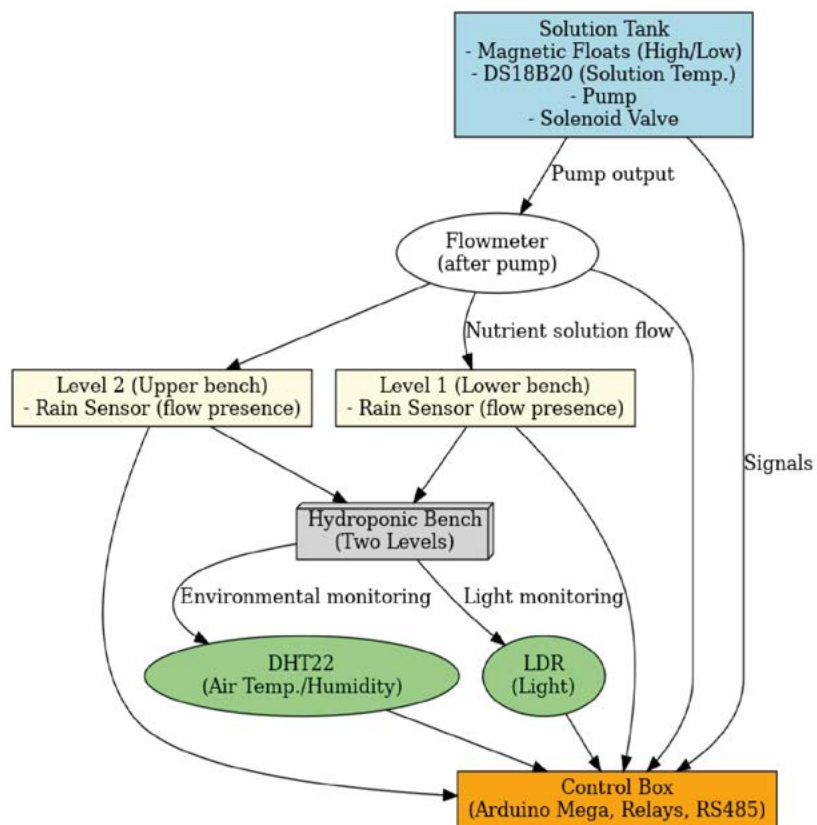


**Figure 4.** Schematic (left) and real installation (right) showing the location of sensors and actuators in the hydroponic bench system.

### Float and DS18B20 (Temperature)

The sensors (float and temperature) were mounted in the solution tank according to the procedure below: In the solution tank with a capacity of 500 l, two level buoys were mounted 20 cm apart to check and maintain the solution level, as this distance keeps the level safe for the solution pump, and a DS18B20 temperature sensor to monitor the temperature of this solution. At first, the cables had to be spliced due to the distance, and they were placed in a 20 mm conduit pipe from the solution box to the control center inside the greenhouse to protect and make the data collected more reliable.

All sensors and actuators were installed in the greenhouse with mechanical protection to ensure measurement reliability and durability. Float switches and the DS18B20 temperature sensor were placed in the nutrient solution tank, with conduits protecting cables from humidity, Azmi (2024). The solenoid valve and flow meter were protected with PVC casings, while rain sensors (used as flow detectors at each cultivation level) and the DHT22 (temperature and humidity) received customized housing to minimize the effect of direct sunlight and rain, Azmi (2024). The LDR was positioned inside the acrylic control box, which provided sufficient protection without interfering with light measurement. These precautions ensured long-term sensor performance under greenhouse conditions.



**Figure 5.** Layout of the hydroponic greenhouse bench showing the installation of sensors (DS18B20, DHT22, LDR, rain sensors, flowmeter, magnetic floats) and actuators (pump and solenoid valve).

### **TLL-RS-485 Human-Computer Interface**

This session will show the screens (interfaces) created in ScadaBR, showing all the greenhouse-operator interaction in real time and the benefits that this tool can provide. The details of installation, software configuration and each screen are described step by step in the work by. Firstly, to access the hydroponic greenhouse's supervisory system, the user must enter their login and password at the "localhost:8080/ScadaBR/" link. In the software (ScadaBR), some screens were created for interaction with the user via the web interface to visualize all the climate parameters with the operation of the hydroponic greenhouse actuators in real time, with values updated every minute. The main screen (Watch List menu) on entering the software contains information on all the variables present in the project. The ScadaBR supervisory system allowed real-time monitoring of climate parameters and actuators, with alarms and data logging accessible via web interface.

### **Alarm Screen**

The alarm was developed to signal to the owner sensor readings that are outside the parameters recommended for growing coriander in hydroponic conditions. Once the alarm detects values outside the recommended range for the plant's development or the hydroponic system's programmed operation, it will send an online signal to the mobile device and light up a Red, Green, Blue (RGB) LED in the central monitoring box located inside the greenhouse, remaining on until the sensors detect the ideal conditions pre-established in the project. As there are several sensors taking readings, only one RGB LED was installed as an alarm for all the sensors, so as not to fill the central box with LEDs by placing one LED for each sensor. Once the RGB LED, which contains three colors, is lit (Blue for the flow and solution presence sensors on both levels, Green for luminosity and humidity, Red for the ambience and solution box temperature), the owner must access the online page to identify in more detail which parameters are outside the recommended range and take corrective action, Nikolov *et al.* (2023).

The parameters used to light the LED were determined as follows: Humidity <30%, luminosity <200, ambience and solution temperature >29 °C and flow meter together with the other two solution presence sensors >15 min without detecting nutrient solution. Any measurement outside these ranges will cause the LED to remain on until it normalizes.

### **Signal LEDs**

Its purpose is to signal adverse situations in the solution box. The green LED will light up when it is full and as the solution level drops, the green LED will turn off and the red LED will light up, signaling that the solution is at a level between the two floats installed in the box. As soon as this level reaches the lower float, the next red LED will turn on, indicating that the solenoid has been triggered to fill the box with water. The two red LEDs will remain on until the water level reaches the upper float to turn them off and the green LED will turn on again, Foster *et al.* (2010); Rajaseger (2023). At this stage, the aim of the project was to monitor all the operating conditions of the hydroponic bench from a long distance, giving the operator more freedom and convenience. To this end, interfaces were created in the software to better meet the project's proposal.

## RESULTS AND DISCUSSION

### Flow Meter

The average flow rate measured was 4.7 L/min during each pump activation. This value is consistent with recommended flow rates for leafy vegetable hydroponics, typically ranging from 4 to 6 L/min to ensure uniform nutrient distribution, Resh (2001); Mwaniki *et al.* (2024). The agreement with literature supports the hypothesis that low-cost flow sensors can provide reliable measurements comparable to commercial monitoring systems. This parameter is critical in hydroponic systems, as the solution pump acts as the system's heart, ensuring proper flow and pressure for nutrient distribution across the cultivation benches, Kurniasari *et al.* (2025). The pump operated in 15-minute on/off cycles during the day, and every two hours at night, consistent with best practices for energy efficiency and crop physiology.

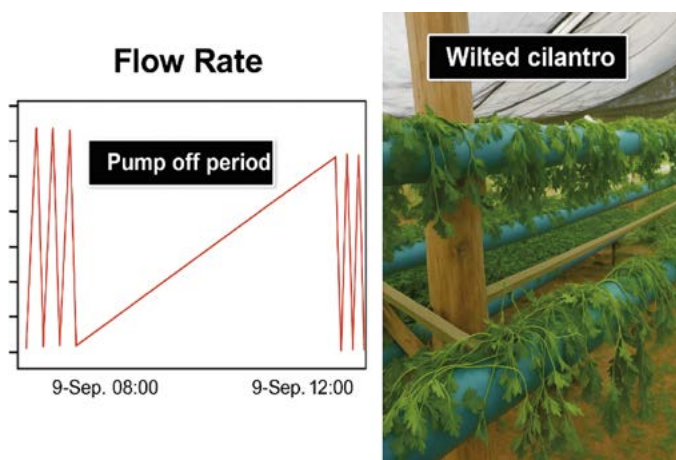
An important system feature was the alarm, which was triggered (blue LED and web notification) when the pump failed to operate for more than 15 minutes. Prompt operator intervention prevented crop loss, demonstrating the value of automated supervision, Aselek *et al.* (2022); Kurniasari *et al.* (2025).

### Flow Presence Sensors

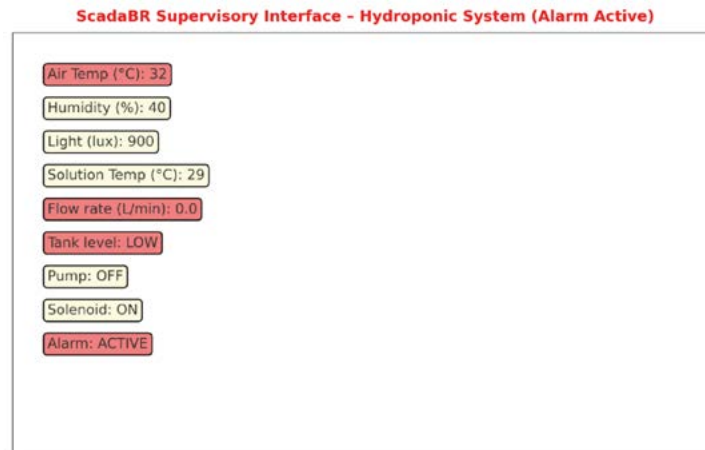
Rain sensors were used as tactile flow sensors at each cultivation level to detect the presence of the nutrient solution, Sail (2024); Kurniasari *et al.* (2025). The system alarm was programmed to activate if no flow was detected for more than 15 minutes, alerting the operator to potential issues such as pressure drops or leaks.

### Temperature and Humidity

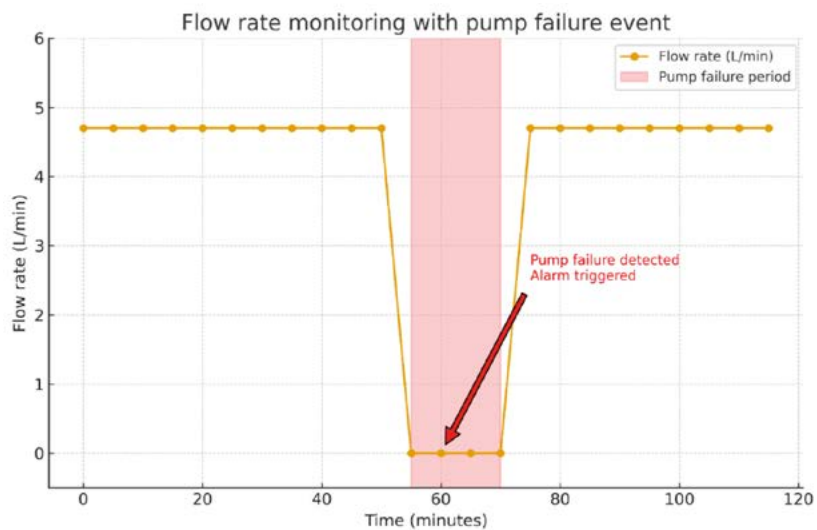
Ambient temperature inside the greenhouse, measured by the DHT22 sensor, showed minimums of 17 °C at night and maximums between 27 °C and 32 °C during late morning and early afternoon, which are suitable for coriander cultivation. For temperatures above 29 °C, a red LED was triggered both locally and on the web interface, Nikolov *et al.* (2023).



**Figure 6.** Flow rate monitoring during a pump failure event (left), indicating irrigation interruption, and visual evidence of cilantro wilting as a consequence (right).



**Figure 7.** ScadaBR HMI screen during an alarm event, showing critical values (air temperature above 30 °C, zero flow rate, low tank level), with pump OFF and solenoid ON. The alarm status is highlighted as ACTIVE.



**Figure 8.** Temporal flow record (L/min) showing a pump failure event between 55 and 70 minutes, during which the alarm was triggered.

Relative humidity remained above 50% throughout the monitoring period, favorable for crop development and reducing excessive evapotranspiration. According to Rouphael and Colla (2019), coriander and similar leafy crops show optimal growth between 18 and 30 °C with relative humidity above 50%. In this study, 92% of recorded values remained within this recommended range, indicating adequate system sensitivity and control. These findings reinforce the reliability of low-cost sensors for environmental monitoring in greenhouses, Kushawaha (2024).

### Solution Temperature

The temperature of the nutrient solution, monitored by the DS18B20 sensor, ranged from 16 °C at night to 25 °C during the hottest periods of the day. This stability was

aided by the solution tank being buried 20 cm underground and covered, minimizing direct solar heating.

### **Solution Level**

Two level sensors spaced 20 cm apart in the solution tank enabled reliable detection of high and low water levels. When the solution dropped below the lower float, the system automatically activated the solenoid to refill the tank, maintaining operational safety for the pump and ensuring adequate solution supply, Uddin *et al.* (2022); Mwaniki *et al.* (2024). Nutrient consumption could be calculated based on the number of solenoid activations, as each refill volume was known and logged by the ScadaBR system.

### **Luminosity**

The LDR sensor provided data on light intensity, with highest levels observed between 9:00 and 14:00. This information can support future integration of artificial lighting or shading strategies.

### **System Performance**

The system enabled real-time visualization of all monitored parameters and status of actuators via a web interface, including graphical trends. The alarm system, through RGB LEDs and notifications, efficiently alerted the operator to abnormal conditions, minimizing risks, Mwaniki *et al.* (2024). Despite minor hardware failures (a faulty RTC timer and DHT22 sensor, both replaced), the platform performed robustly, providing continuous automated monitoring at low cost. In addition to qualitative observations, quantitative assessment of system performance indicated that alarms were triggered within an average of 40 seconds after sensor thresholds were exceeded. The overall uptime of the monitoring platform was 97% during the test period, despite minor hardware replacements. These metrics demonstrate that the developed system can achieve operational performance comparable to higher-cost commercial platforms. Compared with previous works that focused on a limited set of parameters such as pH and EC only (Domingues *et al.* (2012); Untoro and Hidayah (2022), the present system integrates six environmental and solution-related variables into a single supervisory platform. This broader coverage improves crop safety, since failures in temperature, luminosity, or solution flow can also be detected in real time. This broader scope of monitoring demonstrates a higher degree of integration than previously reported in literature, highlighting the novelty of combining environmental and solution-related parameters in a unified low-cost platform.

### **System Reliability and Response**

Real-time feedback and alarms significantly reduced risks associated with pump failure or low nutrient solution levels. The operator could act promptly to prevent crop losses. This highlights the importance of redundant sensors and clear alarm signals in critical agricultural automation. While the rapid detection of pump failures and abnormal solution levels provides strong evidence in favor of the hypothesis, occasional hardware malfunctions (*e.g.*, RTC timer, humidity sensor) highlight potential vulnerabilities of relying solely on low-

cost devices. This suggests that redundancy and sensor calibration protocols are necessary to further improve long-term reliability, Domingues *et al.* (2012); Mwaniki *et al.* (2024). Another innovative aspect is that, unlike many IoT-based prototypes reported only under laboratory or simulated conditions, this system was tested under real greenhouse operation with coriander, demonstrating practical feasibility in a tropical environment.

### **Environmental and Resource Management**

Continuous monitoring of temperature, humidity, and solution parameters ensured that the greenhouse environment remained within optimal conditions for coriander growth. Automated actuation based on thresholds (such as activating solenoids or LEDs) minimized the need for manual interventions, as supported by previous research, Costa *et al.* (2012); Domingues *et al.* (2012). The logging of water consumption through solenoid activations enabled precise calculation of nutrient needs, reducing waste and improving sustainability.

### **Scalability and Adaptability**

The open-source and low-cost design proved scalable and adaptable. With minor modifications, the system can integrate additional sensors (pH, EC) or be applied to other agricultural contexts, such as poultry or aquaculture farming. The modularity of the platform and ease of web-based monitoring democratize access to advanced crop automation for small and medium-sized producers, Almeida & Ferreira (2022).

### **Limitations and Future Prospects**

While the system showed robust performance, timely maintenance of sensors is required, and the software could benefit from more advanced analytics and decision-making capabilities (*e.g.*, predictive alerts, automated pH/EC control). Future expansion may include mobile app notifications and integration with machine learning algorithms for predictive crop management, Almeida & Ferreira (2022). This study demonstrates that accessible automation platforms can significantly improve hydroponic crop management, reduce labor requirements, and enhance system reliability. The results provide a solid foundation for broader application and continued technological advancement in sustainable agriculture. Another limitation is that the system was tested with coriander in one greenhouse only; future studies should test scalability in different crops and environments.

### **CONCLUSIONS**

The implementation of an automated monitoring and control system in a hydroponic greenhouse demonstrated the potential to improve operational efficiency, data accessibility, and crop management. By integrating low-cost sensors, open-source hardware (Arduino Mega 2560), and ScadaBR supervisory software, it was possible to monitor temperature, humidity, luminosity, flow rate, and solution level in real time, with responsive actuators triggered when thresholds were exceeded. The system maintained nutrient solution flow at an average of 4.7 L/min, kept solution temperature between 16 and 25 °C, and successfully activated alarms in cases of pump malfunction and low tank levels. These results support

the proposed hypothesis, showing that affordable automation solutions can provide reliable data acquisition and supervision under real greenhouse conditions. In addition, the web-based human-machine interface offered remote access and control, increasing operator autonomy and optimizing labor use. A key contribution of this study lies in demonstrating that a fully open-source, low-cost solution can achieve reliable monitoring and control under real cultivation conditions, offering a practical alternative to high-cost commercial systems. The originality of this study lies in the integration of multiple variables into an open-source supervisory platform tested under real cultivation conditions, providing empirical evidence that such systems can bridge the gap between academic prototypes and practical agricultural adoption.

Although minor hardware issues (*e.g.*, RTC timer and humidity sensor malfunctions) occurred, they did not compromise overall system functionality. However, these events highlight the need for redundancy and calibration protocols when employing low-cost devices. Moreover, since the study was limited to one crop and one greenhouse, the conclusions should be considered within this experimental scope. Overall, the findings indicate the feasibility of using open-source and low-cost supervisory systems for hydroponic automation, particularly for small and medium-sized producers. Future research should include long-term testing, integration of additional parameters such as pH and EC, and evaluation across different crops and environments to strengthen evidence and confirm scalability.

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