

Automated system with ESP32 for monitoring vertical hydroponic farming and air quality

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ABSTRACT

Urban population growth has increased air pollution levels and adversely affected public health, highlighting the need for sustainable solutions in densely populated cities. While urban agriculture and monitoring technologies offer alternatives for improving the climate, there is limited integration of automated systems to optimize hydroponic vertical farming. Research shows that urban agriculture and vertical hydroponic farming contribute to improving the urban climate through the integration of sensors and intelligent control models. This research proposes a low-cost automated system based on ESP32 for hydroponic crops and environmental monitoring, integrating sensors, actuators, and threshold-based control algorithms with wireless connectivity to regulate agro-environmental variables. A cyclical control system is implemented that periodically evaluates variables such as temperature, substrate moisture, pH, and turbidity with configurable thresholds, automatically activating actuators to maintain optimal growing conditions. The results show that automated irrigation control, real-time monitoring, and CO₂ reduction were achieved under controlled conditions, demonstrating its usefulness for environmental management. Future work proposes integrating predictive algorithms with automatic alerts.

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1. INTRODUCTION

Currently, the world's urban population is increasing, leading to higher energy consumption, industrial activity, and motorized transport, thus increasing air pollution [1], [2]. Studies on particulate matter (PM_{2.5}) exposure and cardiorespiratory mortality in Lima [3], [4], demonstrate the need to implement strategies to reduce the effects of urban pollution, which causes chronic respiratory diseases [5], [6]. In addition, most people in urban environments breathe polluted air, and that millions of premature deaths occur annually due to poor air quality [7]. Without the adoption of monitoring and sustainability technologies, cities will face greater risks to health and the environment [8], [9].

In the case of urban agriculture, real-time environmental monitoring and the use of smart technologies appear as technological solutions to the described problems of continuity and monitoring [10], [11]. Furthermore, urban agriculture initiatives have emerged as a response to limited land use and increasing food insecurity [12]. Although urban agriculture projects have been promoted, these have not been integrated with technological systems [13]. In response to this problem, urban agriculture is a strategy that contributes to food security, improves the urban microclimate, and enhances air quality. Furthermore, urban farming systems can address the scarcity of green spaces [13], [14]. Vertical farms, in particular, purify the air,

increase urban biodiversity, and reduce the urban heat island effect [11], [15], thus contributing to green infrastructure integrated into the urban environment [16].

Research has demonstrated the application of ESP32-based systems for urban air quality monitoring [17], [18], and their performance can be validated using sensor networks [19]. ESP32-based internet of thing (IoT) devices demonstrate their ability to process data and transmit information to cloud platforms [20], [21]. Methodologies for integrating IoT systems for monitoring hydroponic crops are also described, using sensors for CO₂, temperature, substrate moisture, and particulate matter [22], [23], as well as techniques for integrating linear congruential generator-based boosting (LCGM-Boost) regression models to predict crop yields [24]. Hydroponic systems can eliminate dependence on traditional soil and allow for control of nutritional variables [25]. Furthermore, productive efficiency can be improved through the automation of irrigation and nutrient dosing systems [26], [27]. In some cases, systems are being considered that integrate real-time pH and electrical conductivity sensors [28], energy control with photovoltaic modules [29], monitoring of PM_{2.5} and PM₁₀ variables to identify suitable locations for automated vertical farming [30], or nutrient and lighting management in hydroponic systems [31]. The viability of control systems for aeroponic systems [32] and sensor-based irrigation for vertical crops has also been demonstrated, including monitoring for CO, NO_x, NH₃, and CH₄ [33].

While progress has been made in automated urban agriculture and environmental monitoring, a significant gap exists in the literature regarding systems that integrate hydroponic vertical farming with the quantitative assessment of their impact on urban air quality (Table 1). Therefore, this research demonstrates the implementation of a prototype of vertical hydroponic cultivation by integrating environmental sensors, actuators for valve control and automation algorithms, demonstrating the viability of the system to reduce urban air pollution.

Table 1. Related systems described in papers

Reference	System	Sensing	Control type	Air-quality
Pineda-Tobón <i>et al.</i> [17]	ESP32	AQ only	—	Yes
Montaño-Blacio <i>et al.</i> [22]	IoT monitoring	CO ₂ , temp., humidity, and PM	Monitoring only	Partial
Hernández-Morales <i>et al.</i> [23]	IoT protected cultivation	Environmental	Monitoring only	No
Rajendiran and Rethnaraj [24]	Aeroponic+IoT	Yield prediction	Predictive (ML)	No
This study	ESP32 hydroponic+AQ	Moisture, pH, turbidity, temp., and CO ₂	Threshold-closed-loop	Yes

Therefore, this research proposes a low-cost prototype based on the ESP32 that integrates threshold-based closed-loop irrigation and solution control with continuous CO₂ monitoring within a vertical hydroponic module. The main contributions of this study are: i) an integrated hardware and firmware architecture that combines the detection of substrate moisture, pH, turbidity, solution temperature, and CO₂ with coordinated actuator control on a low-cost platform; ii) a threshold-based closed-loop control algorithm for irrigation, pH correction, and temperature regulation; and iii) a preliminary prototype-scale assessment of the system's potential contribution to indoor CO₂ variation as a feasibility indicator.

2. METHOD

Four stages were determined for the monitoring and control prototype: mechanical and irrigation, electronic, control firmware, and monitoring platform. To regulate variables such as substrate moisture, temperature, and nutrients, and threshold-based closed-loop algorithms are used for control and monitoring, with IoT connectivity (Figure 1).

The system has an ESP32-based control module that operates on a cyclical process (every 5 to 30 minutes) analyzing and evaluating the variables measured by the sensors to determine when to activate the actuators. Thresholds are used to regulate temperature (T), substrate moisture (H), pH (pmin, pmax), and turbidity, with a threshold value of "W". This analysis allows for irrigation, heating, or liquid solution renewal processes to improve crop growth conditions. Furthermore, as shown in the flowchart, these parameters are adjusted using a software interface for monitoring, time-based analysis, and air quality assessment (Figure 2).

The flowchart illustrates the periodic decision cycle for evaluating the measured variables (vT, vH, vpH, vW) based on thresholds (T, H, pmin, pmax, W) to determine corrective actions. If the temperature exceeds its threshold (vT < T), the heating element and irrigation are activated; if the substrate moisture exceeds the threshold (vH < H), substrate is pumped; and for pH, if it falls outside the acceptable range (vpmin < pmin or vpmax > pmax), water or substrate is injected accordingly. In the case of high turbidity (vW > W), a process of discarding and renewing the nutrient solution is executed. This algorithm allows for the maintenance of optimal growing conditions (Figure 3).

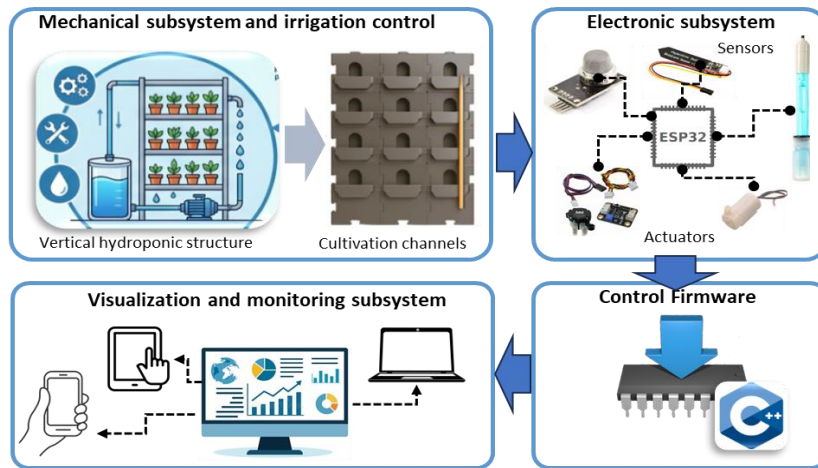


Figure 1. General diagram of the control system

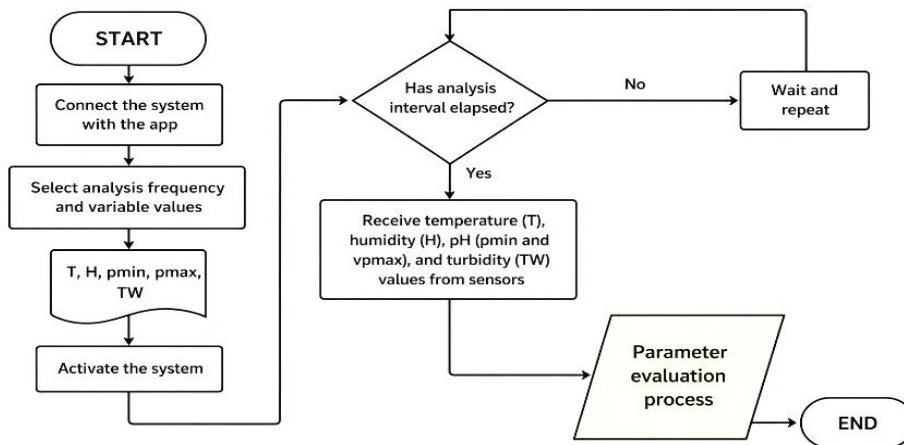


Figure 2. System operation flowchart

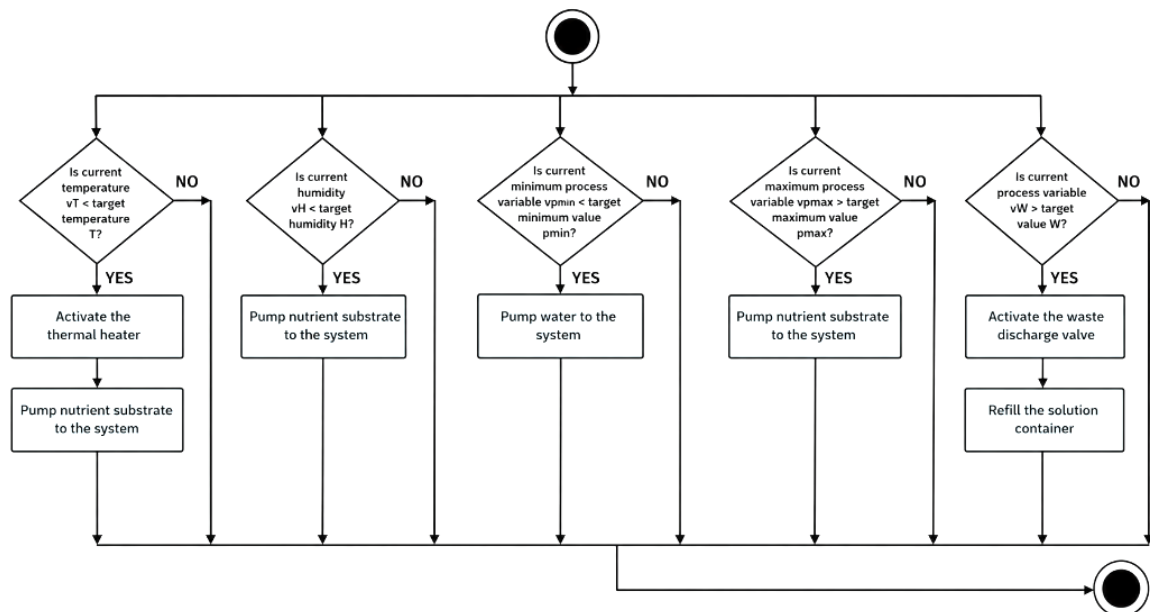


Figure 3. Parameter evaluation procedure

2.1. Mechanical subsystem and irrigation control

The structure utilizes PVC due to its strength and the weight of the electronic components, such as the ESP32 (18 to 40 grams), the pH sensor (360 grams), the substrate moisture sensor (5 to 20 grams), and other sensors. Furthermore, the structure is designed to maintain the plant's stability and volume (Figure 4). The irrigation stage is located behind each module (Figure 5), and the substrate outlet (Figure 5(a)) has a section of the irrigation components exposed outside the structure (Figure 5(b)). Additionally, the automated irrigation process is integrated into a vertical hydroponic growing structure with tiered growing platforms connected by pipes. Branch lines direct water to each tray for uniform irrigation (Figure 6).

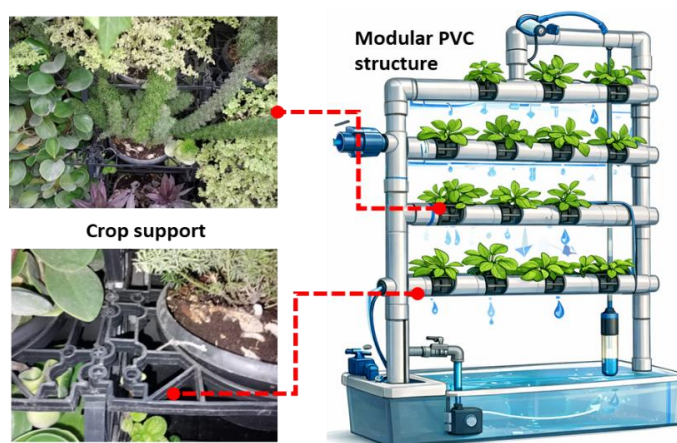


Figure 4. Location of the joints between modules of the structure

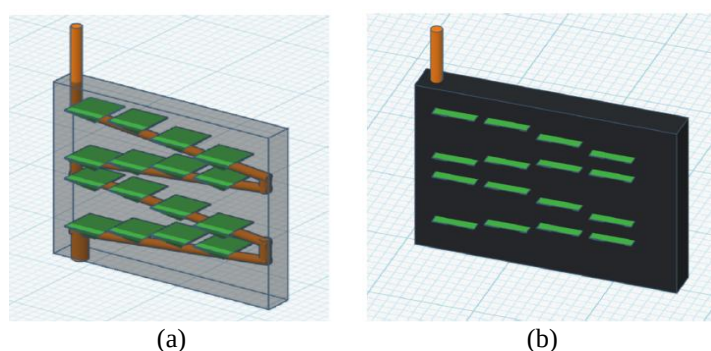


Figure 5. Proposed design for the automatic irrigation stage with; (a) internal view and (b) external support view

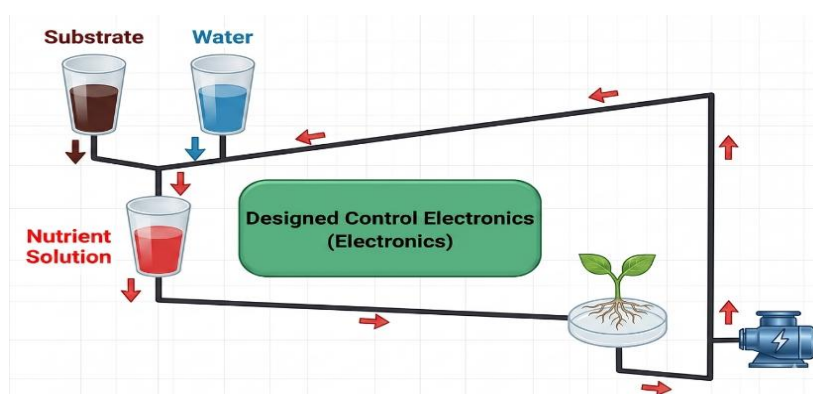


Figure 6. Irrigation system plan for the prototype

2.2. Electronic subsystem

The electronic subsystem is the critical component for data acquisition, signal processing, and actuator activation based on environmental and substrate conditions. It integrates physical variable sensors, an ESP32-based microcontroller, and control modules. The information flow encompasses the sensing stage through to the execution of corrective actions using a closed-loop control scheme.

A capacitive moisture sensor measures the substrate's water content to trigger irrigation, a DFRobot SEN0161-V2 pH sensor monitors the nutrient solution's acidity and allows for correction of deviations, and a DFRobot SEN0189 turbidity sensor detects the presence of particles to activate drainage and renewal. Additionally, a DS18B20 temperature sensor is used for thermal control of the nutrient solution (immersed sensor). Finally, an MQ135 air quality sensor measures gas concentrations such as CO₂ (Figure 7).

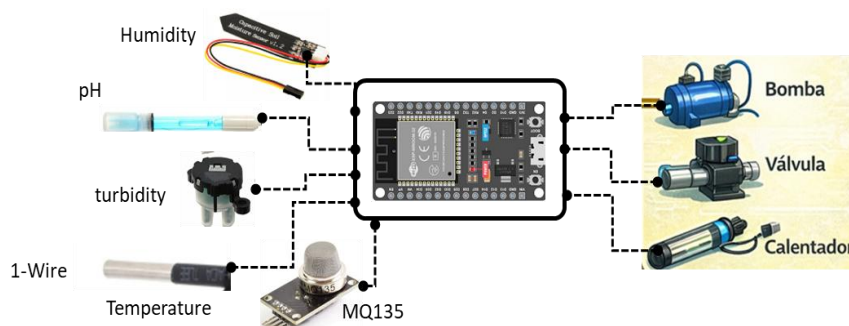


Figure 7. Block diagram of the electronic subsystem

For hydroponic control, actuator devices are used, such as a mini-pump that circulates liquid solutions to improve crop growth, and a pulse-controlled solenoid valve to regulate water circulation. A submersible heater is also integrated to control the temperature. The ESP32 microcontroller acquires data via analog or digital protocols using a sensor such as the DS18B20 for temperature, turbidity, substrate moisture (GPIO34), pH, and air quality (MQ135) (Figure 8).

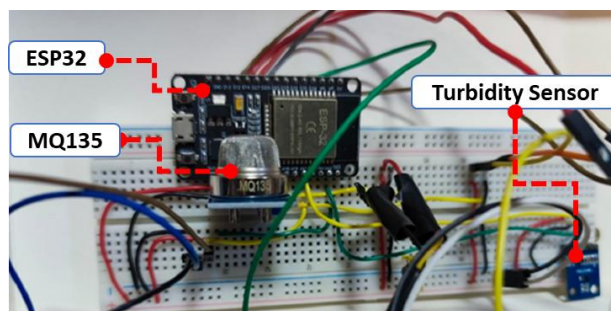


Figure 8. Integrated electronic subsystem components

2.3. Electronic subsystem firmware

The control and monitoring pins with analog and digital protocols for sensors and actuators are determined using the ESP32 module. Data from the DS18B20 temperature sensor is acquired using the OneWire (1-Wire) protocol, while the capacitive moisture sensor, pH, turbidity, and MQ135 sensors are read through the ESP32's analog-to-digital converter (ADC), according to Table 2. Universal asynchronous receiver transmitter (UART) is used for local debugging and Wi-Fi with the message queue telemetry transport (MQTT) protocol for monitoring.

To perform the control, the data acquired from the sensors is evaluated in a closed loop, comparing the measurements and activating valves or flow regulators when variations outside the appropriate crop growth ranges are detected (Table 3). Data acquisition is carried out using I2C communication protocols for the digital sensors, and UART and Wi-Fi protocols for remote monitoring and control. Threshold ranges were defined based on general agronomic guidelines for the cultivated ornamental foliage species (Fittonia, Oxalis, and Tradescantia).

Table 2. Connecting components to the ESP32

Component	Type	ESP32 pin	Technical notes
Capacitive moisture sensor	Analog input	GPIO 34	Input only; no output capability.
pH sensor (DFRobot SEN0161-V2)	Analog input	GPIO 35	Requires signal conditioning module.
Turbidity sensor (DFRobot SEN0189)	Analog input	GPIO 32	Stable reading using ADC1.
DS18B20 temperature sensor	OneWire digital	GPIO 4	Requires 4.7 kΩ pull-up resistor.
MQ135 gas sensor	Analog input	GPIO 23	Input only; no output capability.
Mini submersible pump (2.5 V–6 V)	Digital output	GPIO 22	Add flyback diode.
5 V latching solenoid valve	Digital output	GPIO 19	Use diode protection.
5 V USB submersible heater	Digital output	GPIO 18	Controlled via SSR relay or power MOSFET.

Table 3. Threshold by sensor

Sensor	Measured parameter	Defined threshold	Justification by species
Capacitive moisture sensor	Substrate moisture	40%–70%	Fittonia, Oxalis, and Tradescantia require constant moisture.
pH sensor SEN0161-V2	Solution acidity (pH)	5.8–6.5	Optimal range for nutrient absorption in ornamental foliage plants.
Turbidity sensor SEN0189	Particles in solution	≤5 NTU	Low values ensure solution clarity and prevent root obstruction.
Temperature sensor DS18B20	Nutrient-solution temperature	18 °C–28 °C	Ideal range for active metabolism without thermal stress.

The threshold-based control system activates irrigation if substrate moisture drops below 40%, triggers the dosing process if the pH exceeds 6.5, and activates the heater if the temperature falls below 19 °C. Because each variable is re-measured during the following control cycle and the updated reading determines the next actuation decision, the system implements a closed-loop threshold-based control scheme rather than an adaptive one.

2.4. Visualization and monitoring subsystem

A monitoring and control interface was designed using data from acquired sensors and the status of actuators. Data transmission was performed using Wi-Fi communication (based on the WiFi.h library) via the MQTT protocol (with the PubSubClient.h library). The firmware program executes processes in a repetitive cycle of data acquisition, validation, processing, and actuation. Additionally, sensor readings are recorded, filtering out noise or anomalies before comparing them to control thresholds (Figure 9).

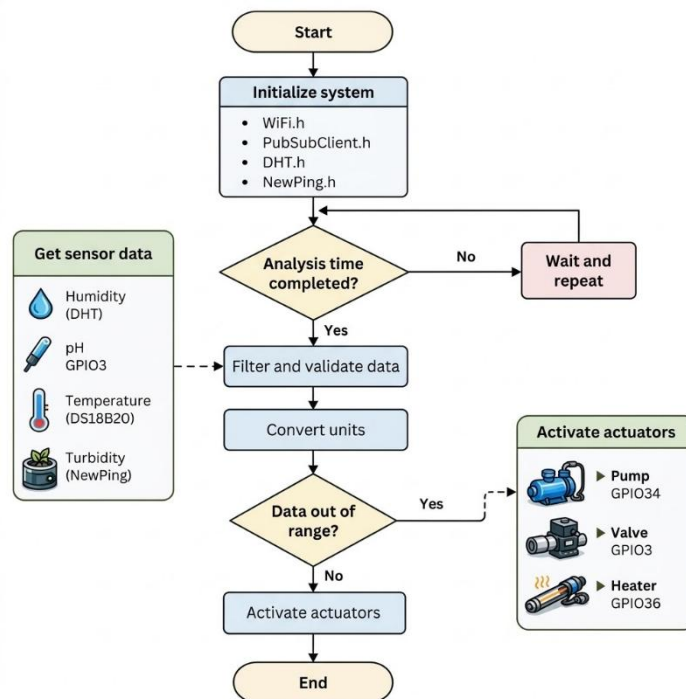


Figure 9. Firmware data acquisition process

A key performance indicator (KPI) panel is used, considering metrics such as the percentage of time in optimal range (PTRO), specific water consumption, and system availability. Furthermore, monitoring and quantifying sensor data variations allows for determining the contribution to urban environmental improvement with regard to CO₂ and PM2.5 levels.

This is achieved using stat panels in Grafana, employing JSON configuration documents to display each KPI. The JSON structure indicates the panel's position on the grid (gridPos), and the expr field generates the server query to retrieve the data. This visualization displays data acquired from the ESP32 via Bluetooth communication, considering 30-second update intervals (Figure 10).



Figure 10. Initial interface visualization proposal

2.5. Sensor calibration procedures

The DS18B20 digital temperature sensor has a manufacturer's accuracy of ± 0.5 °C in the range of -10 °C to $+85$ °C. The SEN0161-V2 pH sensor was calibrated using standard buffer solutions of pH 4.01, 6.86, and 9.18, resulting in a calibration of ± 0.1 pH units. The DFRobot SEN0189 turbidity sensor was calibrated using standard NTU values (0, 5, 10, and 20 NTU), with an accuracy of ± 2 NTU. The capacitive substrate moisture sensor was calibrated using the raw ADC output under two reference conditions (sensor in air=0% and sensor fully submerged=100%). Finally, the MQ135 gas sensor was calibrated with respect to the CO₂ value after a preheating period of 24 to 48 hours, as specified by the manufacturer.

3. RESULTS AND DISCUSSION

3.1. Electronic control subsystem

The system's performance was evaluated using two containers: one for the pure substrate and another for water. Depending on the system configuration, the proportions of substrate and water can be modified in a third container. Through remote configuration or based on pH sensor readings, valves are activated that allow the flow of either water or substrate, resulting in a solution with a specific ratio for the selected plant. In this case, a homemade substrate was prepared consisting of 60% expanded clay (LECA) and 40% rock minerals, specifically extracted from pumice stone. This mixture is dissolved in water at a critical level of 100 mL per 10 g of components. This yields a "pure" substrate that can be diluted as needed for cultivation (Figure 11).

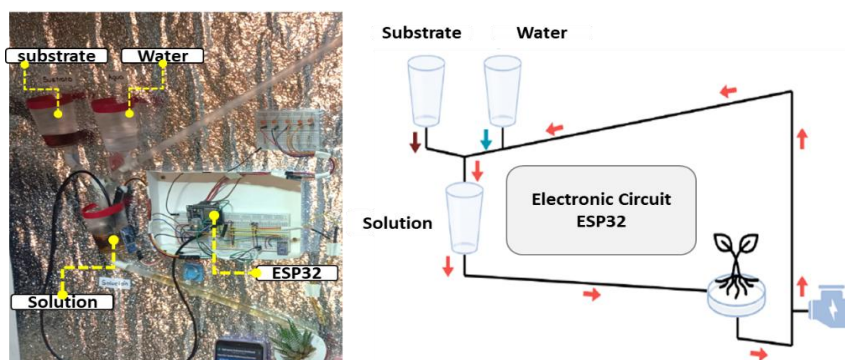


Figure 11. Implemented prototype of the irrigation flow

In the case of sensor integration, data acquisition was validated using digital or analog ports, and actuator control was validated by digitally activating LEDs. First, the substrate moisture sensor detected the lack of irrigation and dryness in the hydroponic system, generating a signal to the ESP32. This then activated the starter pump for solution flow. Furthermore, the control performed with the ESP32 allowed for demonstrating actuator control through the real-time response of the digital outputs (Figure 12).

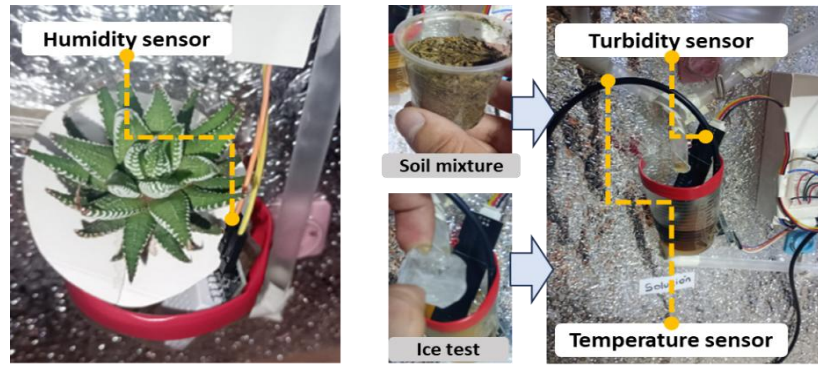


Figure 12. Individual validation of sensor functionality

3.2. Discussion of irrigation control performance

Activation of the irrigation actuator confirms that the threshold-based closed-loop logic functions as expected under laboratory conditions. This behavior is consistent with threshold-based irrigation approaches reported in previous IoT hydroponics studies [22], [23].

3.3. Visualization and monitoring

The KPI panel summarizes the metrics used to evaluate the performance of the automated hydroponic growing system. It includes indicators such as the PTRO, specific water consumption, and system availability (Figure 13). This panel utilizes a dashboard with line graphs, circular gauges, numerical cards, and an alert history. The monitoring subsystem was evaluated considering different sensor states, such as low substrate moisture (Figure 13(a)), low temperature (Figure 13(b)), and acidic pH levels (Figure 13(c)). Finally, CO₂ measurements were taken at ambient CO₂ levels (100% of the CO₂ level) (Figure 13(d)).

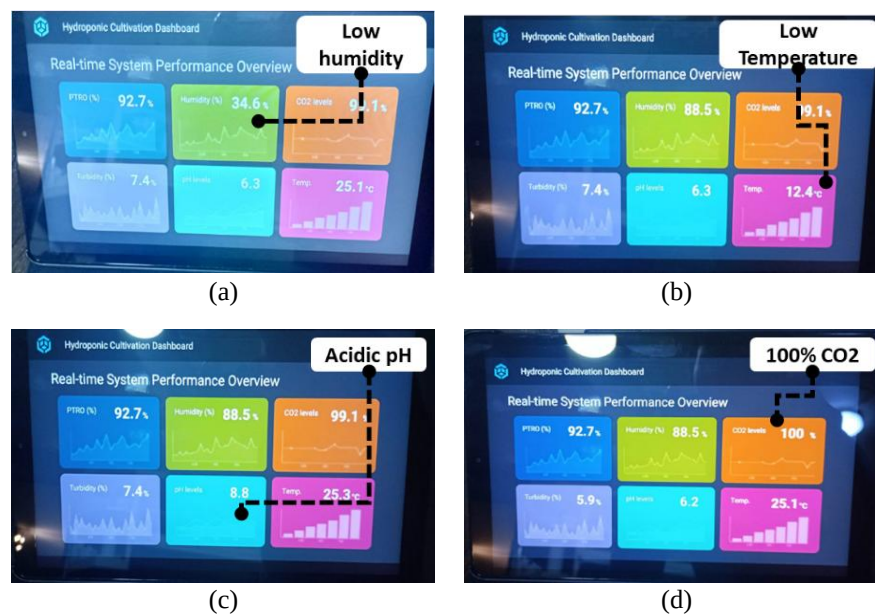


Figure 13. Visualization of different states of the monitoring subsystem for; (a) substrate moisture, (b) low temperature, (c) acidic pH value, and (d) 100% CO₂

3.4. System integration testing

After independently validating the electronics, communication, parameter management, and visualization subsystems, a full system integration test was performed. The irrigation stage was verified in a domestic environment, evaluating the automated control via valves.

The tests were conducted in environments with constant ventilation, lighting, and ambient conditions, with typical CO₂ values between 872 ppm and 802 ppm (Figure 14), which was verified from the remote interface on a smartphone (Figure 14(a)) and an Android tablet (Figure 14(b)). Although the variation is moderate, it corresponds to a prototype with a single growing unit; therefore, a greater impact is expected when the number of modules in operation is scaled up.

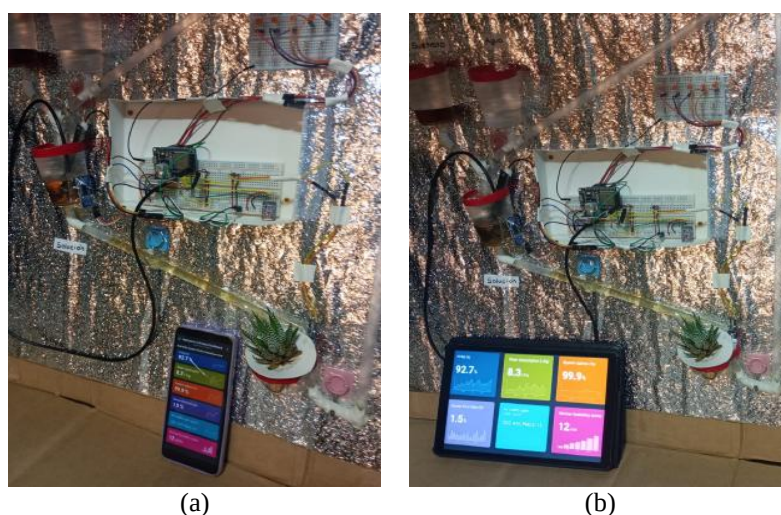


Figure 14. Visualization of the crop monitoring and control platform (POC) using a; (a) smartphone and (b) tablet

In this investigation, experiments and operational tests were conducted over an average of two hours to determine the reduction of CO₂ (from 872 to 802 ppm), obtaining a set of samples to determine the consistency between the readings. Although used as initial observations, these recorded data are considered to have validated the readings provided by the sensors. Table 4 shows a set of data samples captured during the validation tests.

Table 4. Sample measurement results

Trial	Initial CO ₂ (ppm)	Final CO ₂ (ppm)	Duration (h)	Reduction
T1	872	802	2	8.03%
T2	865	796	2	7.98%
T3	880	810	2	7.95%
T4	858	791	2	7.81%
T5	870	803	2	7.70%
Mean±SD	—	—	—	7.89±0.13%

The ESP32 module has a typical current consumption of 160 to 260 mA during Wi-Fi transmission. During the integration test, the system achieved an average round-trip MQTT message latency of less than 1 second and a wireless packet delivery rate exceeding 95%. The PTRO metric indicated that the measured variables remained within their defined optimum ranges throughout the monitoring period.

4. CONCLUSION

The control system successfully integrated irrigation and nutrient management processes in hydroponic crops to stabilize their growth in the face of environmental variations in urban settings. The use of sensors for temperature, pH, turbidity, and gases enabled continuous management of crop conditions through accurate data acquisition and transmission via wireless communication with the ESP32.

Furthermore, the air quality sensor allowed for the evaluation of short-term CO₂ variations under controlled indoor conditions. Within the framework of this single-module test, the system demonstrated its technical feasibility for combining hydroponic cultivation with air quality monitoring. These results should be interpreted as a preliminary indicator at the prototype scale, and not as evidence of mitigating air pollution on an urban scale, which would require replicated, long-term, and larger-scale testing.

Future work recommends integrating predictive algorithms to improve irrigation and nutrient dosage according to crop needs. For monitoring, interfaces can be developed that integrate automatic alerts and message notifications in case of crop risk. Additionally, the prototype can be evaluated in real-world scenarios.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization	I : Investigation	Vi : Visualization
M : Methodology	R : Resources	Su : Supervision
So : Software	D : Data Curation	P : Project administration
Va : Validation	O : Writing - Original Draft	Fu : Funding acquisition
Fo : Formal analysis	E : Writing - Review & Editing	

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Ricardo Yauri, upon reasonable request in this study.

REFERENCES

[1] N. Gouveia *et al.*, “Short-term associations between fine particulate air pollution and cardiovascular and respiratory mortality in 337 cities in Latin America,” *Sci. Total Environ.*, vol. 920, no. 1, pp. 1–7, Apr. 2024, doi: 10.1016/j.scitotenv.2024.171073.

[2] J. L. Kephart *et al.*, “Ambient nitrogen dioxide in 47 187 neighbourhoods across 326 cities in eight Latin American countries: population exposures and associations with urban features,” *Lancet Planet. Heal.*, vol. 7, no. 12, pp. e976–e984, Dec. 2023, doi: 10.1016/S2542-5196(23)00237-1.

[3] J. P. Quispe *et al.*, “Temporal Trend of PM2.5 and the Associated Risk to Human Health in the Lima Metropolitan Area,” *Int. J. Sustain. Dev. Plan.*, vol. 19, no. 12, pp. 4811–4817, Dec. 2024, doi: 10.18280/ijstdp.191228.

[4] V. Tapia, K. Steenland, B. Vu, Y. Liu, V. Vásquez, and G. F. Gonzales, “PM2.5 exposure on daily cardio-respiratory mortality in Lima, Peru, from 2010 to 2016,” *Environ. Heal.*, vol. 19, no. 1, pp. 1–7, Dec. 2020, doi: 10.1186/s12940-020-00618-6.

[5] D. Lsoto, R. Sserunjogi, G. Okello, Y. Chen, J. A. Patz, and J. J. Schauer, “A framework for interpreting air pollution sensor data: Bridging gaps in monitoring, analysis and community action,” *J. Air Waste Manage. Assoc.*, vol. 1, no. 1, pp. 1–12, Mar. 2026, doi: 10.1080/10962247.2026.2635079.

[6] D. R. Peters *et al.*, “Evaluating uncertainty in sensor networks for urban air pollution insights,” *Atmos. Meas. Tech.*, vol. 15, no. 2, pp. 321–334, Jan. 2022, doi: 10.5194/amt-15-321-2022.

[7] S. Maji, S. Ahmed, M. Kaur-Sidhu, S. Mor, and K. Ravindra, “Health Risks of Major Air Pollutants, their Drivers and Mitigation Strategies: A Review,” *Air, Soil Water Res.*, vol. 16, no. 1, p. 10, Jan. 2023, doi: 10.1177/11786221231154659.

- [8] B. Zhai, Q. Duan, J. Liu, H. Zhang, and Z. Xu, "Using machine learning to evaluate the impact of urban development on PM2.5 concentrations and health risks in Chinese cities," *Environ. Impact Assess. Rev.*, vol. 117, p. 108185, Mar. 2026, doi: 10.1016/j.eiar.2025.108185.
- [9] C. Zhan *et al.*, "Impacts of urbanization on air quality and the related health risks in a city with complex terrain," *Atmos. Chem. Phys.*, vol. 23, no. 1, pp. 771–788, Jan. 2023, doi: 10.5194/acp-23-771-2023.
- [10] A. Bhamare and P. Bansal, "Artificial Intelligence and Computer Vision in Sustainable Vertical Farming," in *Artificial Intelligence and Communication Techniques in Industry 5.0*, Boca Raton: CRC Press, 2024, pp. 306–317, doi: 10.1201/9781003494027-19.
- [11] J. Luo, B. Li, and C. Leung, "A Survey of Computer Vision Technologies in Urban and Controlled-environment Agriculture," *ACM Comput. Surv.*, vol. 56, no. 5, pp. 1–39, May 2024, doi: 10.1145/3626186.
- [12] J. Langemeyer, C. Madrid-Lopez, A. M. Beltran, and G. V. Mendez, "Urban agriculture — A necessary pathway towards urban resilience and global sustainability?," *Landsc. Urban Plan.*, vol. 210, no. 1, pp. 1–8, Jun. 2021, doi: 10.1016/j.landurbplan.2021.104055.
- [13] G. N. Yuan *et al.*, "A review on urban agriculture: technology, socio-economy, and policy," *Heliyon*, vol. 8, no. 11, pp. 1–18, Nov. 2022, doi: 10.1016/j.heliyon.2022.e11583.
- [14] P. Pradhan *et al.*, "Urban agriculture matters for sustainable development," *Cell Reports Sustain.*, vol. 1, no. 9, pp. 1–14, Sep. 2024, doi: 10.1016/J.CRSUS.2024.100217.
- [15] M. Nalini and B. Y. Bhuvaneswari, "Computer Vision-Based Innovations for Smart Agriculture and Crop Surveillance," in *Computer Vision in Smart Agriculture and Crop Management*, Wiley, 2025, pp. 1–23, doi: 10.1002/9781394186686.ch1.
- [16] D. Wang *et al.*, "Identification of Priority Implementation Areas and Configuration Types for Green Infrastructure Based on Ecosystem Service Demands in Metropolitan City," *Int. J. Environ. Res. Public Health*, vol. 19, no. 13, pp. 1–19, Jul. 2022, doi: 10.3390/ijerph19138191.
- [17] D. M. Pineda-Tobón, A. Espinosa-Bedoya, and J. W. Branch-Bedoya, "Aquality32: A low-cost, open-source air quality monitoring device leveraging the ESP32 and google platform," *HardwareX*, vol. 20, no. 1, pp. 1–16, Dec. 2024, doi: 10.1016/j.ohx.2024.e00607.
- [18] L. M. Easterline, A. A.-Z. R. Putri, P. S. Atmaja, A. L. Dewi, and A. Prasetyo, "Smart Air Monitoring with IoT-based MQ-2, MQ-7, MQ-8, and MQ-135 Sensors using NodeMCU ESP32," *Procedia Comput. Sci.*, vol. 245, no. 1, pp. 815–824, 2024, doi: 10.1016/j.procs.2024.10.308.
- [19] H. J. El-Khozondar *et al.*, "A smart energy monitoring system using ESP32 microcontroller," *e-Prime - Adv. Electr. Eng. Electron. Energy*, vol. 9, no. 1, pp. 1–10, Sep. 2024, doi: 10.1016/j.prime.2024.100666.
- [20] D. Hercog, T. Lerher, M. Truntiĉ, and O. Težak, "Design and Implementation of ESP32-Based IoT Devices," *Sensors*, vol. 23, no. 15, pp. 1–20, Jul. 2023, doi: 10.3390/s23156739.
- [21] S. Ramadhan, I. Syafalni, N. Sutisna, and T. Adiono, "Implementation of Multi-Hop Mesh Networking Using ESP32 for IoT Communication," in *2024 International Conference on Intelligent Cybernetics Technology and Applications (ICICyTA)*, Dec. 2024, pp. 1055–1059, doi: 10.1109/ICICYTA64807.2024.10912962.
- [22] M. Montaña-Blacio, J. González-Escarabay, Ó. Jiménez-Sarango, L. Mingo-Morocho, and C. Carrión-Aguirre, "Design and deployment of an IoT-based monitoring system for hydroponic crops," *Ingenius*, vol. 2023, no. 30, pp. 9–18, Jul. 2023, doi: 10.17163/ings.n30.2023.01.
- [23] C. A. Hernández-Morales, J. M. Luna-Rivera, and R. Perez-Jimenez, "Design and deployment of a practical IoT-based monitoring system for protected cultivations," *Comput. Commun.*, vol. 186, no. 1, pp. 51–64, Mar. 2022, doi: 10.1016/j.comcom.2022.01.009.
- [24] G. Rajendiran and J. Rethnaraj, "Smart Aeroponic Farming System: Using IoT with LCGM-Boost Regression Model for Monitoring and Predicting Lettuce Crop Yield," *Int. J. Intell. Eng. Syst.*, vol. 16, no. 5, pp. 251–262, Oct. 2023, doi: 10.22266/ijies2023.1031.22.
- [25] A. C. Austria, J. S. Fabros, K. R. Sumilang, J. Bernardino, and A. Doctor, "Development of IoT Smart Greenhouse System for Hydroponic Gardens," *Int. J. Comput. Sci. Res.*, vol. 7, no. 1, pp. 2111–2136, Jan. 2023, doi: 10.25147/ijcsr.2017.001.1.149.
- [26] G. Carrasco *et al.*, "Enhancing Leafy Greens' Production: Nutrient Film Technique Systems and Automation in Container-Based Vertical Farming," *Agronomy*, vol. 14, no. 9, pp. 1–19, Aug. 2024, doi: 10.3390/agronomy14091932.
- [27] T. Thomas, M. S. Biradar, V. P. Chimmad, and B. S. Janagoudar, "Hydroponic cultivation of lettuce: evaluating yield and quality across different systems," *Int. J. Veg. Sci.*, vol. 32, no. 1, pp. 53–70, Jan. 2026, doi: 10.1080/19315260.2025.2555550.
- [28] R. C. Bosman, I. L. van Rooyen, J. Brancken, H. G. Brink, and W. Nicol, "Simultaneous pH and EC control in hydroponics through real-time manipulation of the ammonium-to-nitrate ratio in the nutrient solution," *Sci. Hortic. (Amsterdam)*, vol. 332, no. 1, p. 113185, Jun. 2024, doi: 10.1016/j.scienta.2024.113185.
- [29] W. F. D. Chua, C. L. Lim, Y. Y. Koh, and C. L. Kok, "A Novel IoT Photovoltaic-Powered Water Irrigation Control and Monitoring System for Sustainable City Farming," *Electronics*, vol. 13, no. 4, pp. 1–22, Feb. 2024, doi: 10.3390/electronics13040676.
- [30] A. H. C. Díaz *et al.*, "A Spatio-Temporal Behavior of PM2.5 and PM10 on Changes of Their Concentration Levels in the Metropolitan Area of Lima," *Int. J. Sustain. Dev. Plan.*, vol. 19, no. 10, pp. 4083–4092, Oct. 2024, doi: 10.18280/ijstdp.191036.
- [31] P. B. S. Rao *et al.*, "Automated IoT Solutions for Efficient Hydroponic Farming: Nutrients, PH and Lighting Management," *J. Eur. des Systèmes Autom.*, vol. 57, no. 5, pp. 1273–1283, Oct. 2024, doi: 10.18280/jesa.570503.
- [32] T. M. K. Mohamed, J. Gao, and M. Tunio, "Development and experiment of the intelligent control system for rhizosphere temperature of aeroponic lettuce via the Internet of Things," *Int. J. Agric. Biol. Eng.*, vol. 15, no. 3, pp. 225–233, 2022, doi: 10.25165/j.ijabe.20221503.6530.
- [33] M. Tavan, B. Wee, G. Brodie, S. Fuentes, A. Pang, and D. Gupta, "Optimizing Sensor-Based Irrigation Management in a Soilless Vertical Farm for Growing Microgreens," *Front. Sustain. Food Syst.*, vol. 4, no. 1, pp. 1–12, Jan. 2021, doi: 10.3389/fsufs.2020.622720.

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