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Automated Irrigation System for Hydroponic Greenhouses in Warm and Humid Climates: A Case Study in Manabí, Ecuador

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Abstract: *Hydroponic production in tropical environments requires precise irrigation control due to the high variability of temperature, humidity, and solar radiation. In warm and humid regions, conventional time-based irrigation systems often lead to over-irrigation, water waste, and unstable root-zone conditions. This study proposes and validates an adaptive automated irrigation system for hydroponic greenhouses in tropical climates, with specific applicability to Manabí, Ecuador. The system integrates multisensor monitoring of substrate moisture, ambient temperature, and luminosity, governed by microcontroller-based logic that dynamically activates pumps and solenoid valves according to real environmental thresholds. An applied engineering methodology based on iterative design and electronic simulation in Proteus Design Suite was adopted. Functional performance, robustness, and reliability were evaluated under multiple operational and fault scenarios. Results demonstrate that the system responds in near real time to critical moisture levels, stabilizes substrate conditions, and prevents prolonged water stress. Redundancy mechanisms, flow verification, watchdog recovery, and energy backup transform the controller into a self-supervised and resilient platform. Compared with commercial solutions, the proposed configuration achieves comparable functionality at a substantially lower cost and reduced energy demand, making it suitable for resource-constrained producers. These findings confirm that low-cost adaptive control significantly enhances water-use efficiency and operational stability in tropical hydroponic systems.*

Keywords: *Adaptive irrigation, Hydroponic greenhouse, Tropical agriculture, Embedded control systems, Water-use efficiency.*

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I. INTRODUCTION

Hydroponic agriculture has become an efficient alternative for food production in contexts of high environmental pressure, due to its ability to optimize the use of water and nutrientes (Regmi et al., 2024). However, its performance critically depends on the precise control of microclimatic variables such as substrate moisture, ambient temperature, and light radiation (Al-Shrouf et al., 2023). In warm and humid regions, such as the province of Manabí on the Ecuadorian coast, these variables exhibit high daily and seasonal variability, which increases crop water stress, accelerates evaporation, and compromises plant physiological stability (Yuan et al., 2024). Under these conditions, conventional irrigation systems based on fixed scheduling prove inefficient and tend to generate over-irrigation, resource waste, and reduced productive performance (Ercan Oğuztürk, 2025).

Recent studies indicate that the efficiency of hydroponic systems is directly associated with the ability of irrigation mechanisms to adapt to the actual environmental conditions of the greenhouse (Palma, 2022). Nevertheless, a significant proportion of the technological solutions currently available on the market lack dynamic control mechanisms, relying instead on rigid activation schemes that do not consider the interaction among moisture, temperature, and luminosity (Solís, 2023). This technological gap becomes more pronounced in tropical scenarios, where high relative humidity, elevated temperatures, and intense solar radiation impose operational demands distinct from those of temperate climates, for which most commercial systems have been designed (Kumsong et al., 2023).

In response to this problem, there is a growing need to develop automated irrigation solutions that integrate real-time monitoring, decision-making based on multiple environmental variables, and adaptability to local microclimates, while simultaneously maintaining low implementation and operational costs. These characteristics are especially relevant for small and medium-sized producers, who require robust, scalable, and energy-efficient technologies that do not compromise the economic viability of their production units (Morchid et al., 2026).

Within this framework, the present study proposes and validates an automated irrigation system for hydroponic greenhouses in warm and humid climates, based on the integration of substrate moisture, ambient temperature, and luminosity sensors governed by a programmable microcontroller. The system implements an adaptive control scheme that dynamically activates pumps and valves according to real environmental thresholds, enabling the adjustment of water and nutrient supply to the microclimatic conditions of the greenhouse.

The main contribution of this research lies in the explicit adaptation of the irrigation system to the tropical conditions of Manabí, incorporating a multisensor control approach that improves water-use efficiency, reduces resource waste, and stabilizes the productive environment. Unlike generic solutions based on fixed timing, the proposed system introduces an environmentally sensitive decision model that is low-cost and highly scalable, specifically oriented toward agricultural contexts with technical and economic constraints.

The objective of this study is to design, model, and evaluate an intelligent automated irrigation system for hydroponic crops in tropical greenhouses, demonstrating its technical feasibility and its potential to optimize water use, enhance microclimatic stability, and strengthen productive sustainability in warm and humid environments.

II. EXPERIMENTAL PROCEDURE

1.1 Methodological Design and Validation Approach

The study was conducted using an applied engineering approach focused on the design, implementation, and evaluation of an automated irrigation system for hydroponic greenhouses in warm and humid climates. An iterative and incremental development scheme was adopted, organized in short design–build–test–adjust cycles, in order to reduce technical risks, detect failures at early stages, and optimize system performance prior to full deployment. This approach enabled stepwise validation of both sensor acquisition and actuator response, ensuring operational stability and functional consistency. The evaluation was primarily performed through electronic modeling and simulation of the system, complemented by failure analysis, mitigation strategies, and technical–economic feasibility criteria.

1.2 Operational Requirements of the System

The system was designed to:

(i) Measure substrate moisture, ambient temperature, and luminosity in real time;
(ii) Automate the activation and deactivation of irrigation pumps and solenoid valves;
(iii) Generate alerts in the presence of failures or critical conditions; and
(iv) Record historical data for efficiency analysis.

In addition, non-functional requirements were defined, including low energy consumption, low installation and maintenance cost, an intuitive local interface via LCD display, and adaptability to different greenhouse configurations. These requirements guided the selection of components and the modular architecture of both hardware and software, promoting scalability and ease of maintenance, as recommended in recent low-cost agricultural automation studies (Jiménez, 2024).

1.3 Selection and Integration of Sensors and Actuators

Instrumentation was structured around three primary environmental variables. For substrate moisture, capacitive sensors were selected, prioritizing stability and durability over resistive solutions, particularly due to the constant presence of nutrients and moisture (Valle, 2022). Ambient temperature and humidity were measured using the DHT22 sensor, chosen for its ease of integration and reliable performance in enclosed environments, consistent with agricultural monitoring applications (Aguilar-González et al., 2023). Luminosity was measured using the BH1750 sensor, which provides high-resolution quantification of light intensity, relevant for future strategies involving shading or supplemental lighting control (López et al., 2024).

The actuation stage was designed using 12 V solenoid valves for automatic opening and closing of irrigation lines, and 12 V submersible pumps for the delivery of water and nutrient solution. Load switching was implemented through a relay module, electrically isolating the microcontroller from power currents. Component selection was based on local availability, electronic compatibility, low energy consumption, and favorable cost–performance ratio—key criteria for agricultural applications in resource-constrained contexts (Morales et al., 2024).

1.4 Hardware Architecture

The system was structured around an Arduino Mega 2560 microcontroller, selected for its expanded digital and analog I/O capacity, suitable for multiple irrigation zones and future extensions. Moisture sensors were connected to analog inputs, while the DHT22 and BH1750 sensors were integrated via digital interfaces, including I2C communication for the light sensor. Actuators were controlled through digital outputs connected to the relay module. A 12 V power supply was used for pumps and valves, with voltage regulation to 5 V for the microcontroller and logic peripherals. Local interaction was provided through a 20×4 LCD display with I2C interface, used to visualize environmental variables and irrigation status. As a connectivity extension, an ESP8266 WiFi module was integrated via UART communication, enabling future remote monitoring and data logging, in line with smart irrigation trends (Solís, 2023).

1.5 Software Architecture and Control Logic

Firmware was developed in the Arduino IDE using structured C++ programming and dedicated libraries for data acquisition (BH1750). The software was organized into functional modules: sensor reading and filtering, threshold evaluation, actuator control, and LCD visualization. Control logic was defined through environment-based rules: when substrate moisture falls below a defined threshold, the system activates the pump and opens the corresponding irrigation valve; in the presence of elevated temperature, the system generates an alarm signal or activates mitigation mechanisms in extended versions; and under low luminosity, supplemental lighting may be enabled if supported by the hardware.

As a formal representation of the control logic, a Ladder-type scheme was defined, with inputs associated with low-moisture, high-temperature, and low-luminosity events, and outputs associated with pump activation, valve control, and alarms. This structure facilitates future migration of the control layer to industrial PLCs or hybrid systems, maintaining a traceable and verifiable logic framework.

1.6 System Modeling and Simulation

Initial verification was conducted through simulation in Proteus Design Suite, modeling the microcontroller, sensors, relay module, and loads equivalent to pumps and valves. Power interface circuits were designed using transistors to drive relays and protect microcontroller outputs, including isolation considerations and inductive load handling. Within the simulation environment, several operational scenarios were evaluated:

(i) Low moisture, verifying automatic activation of pump and valve;
(ii) High temperature, validating alarm or mitigation activation; and
(iii) Luminosity variation, verifying BH1750 response and associated logic.

This stage enabled verification of functional coherence and anticipation of robustness requirements prior to physical deployment.

1.7 Reliability Strategies and Failure Mitigation

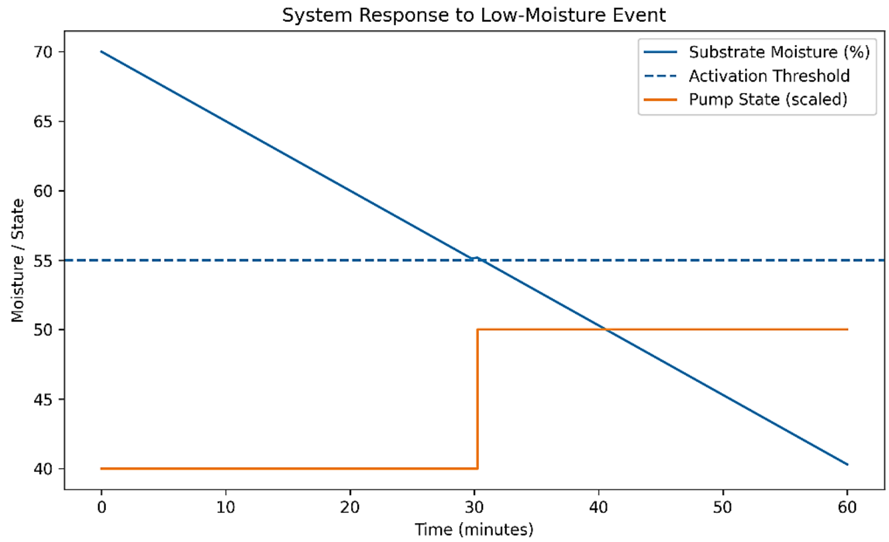
To enhance system reliability, common failures in agricultural environments were considered. In the event of sensor failure, sector-based redundancy (dual moisture sensors) was proposed to enable comparison and detection of anomalous readings. For pump or valve failures, the integration of flow sensors was proposed to verify that activation results in actual fluid movement, enabling alerts for mechanical failure or blockage. For software faults or microcontroller lockups, a watchdog timer strategy was incorporated to enable controlled automatic resets. Finally, to address power outages, the use of compact UPS units or battery backups was proposed, preventing critical irrigation interruptions during periods of high thermal demand, a key requirement in tropical hydroponic systems (Solís, 2023).

III. RESULTS AND DISCUSSIONS

3.1. System Performance under Simulated Operating Conditions

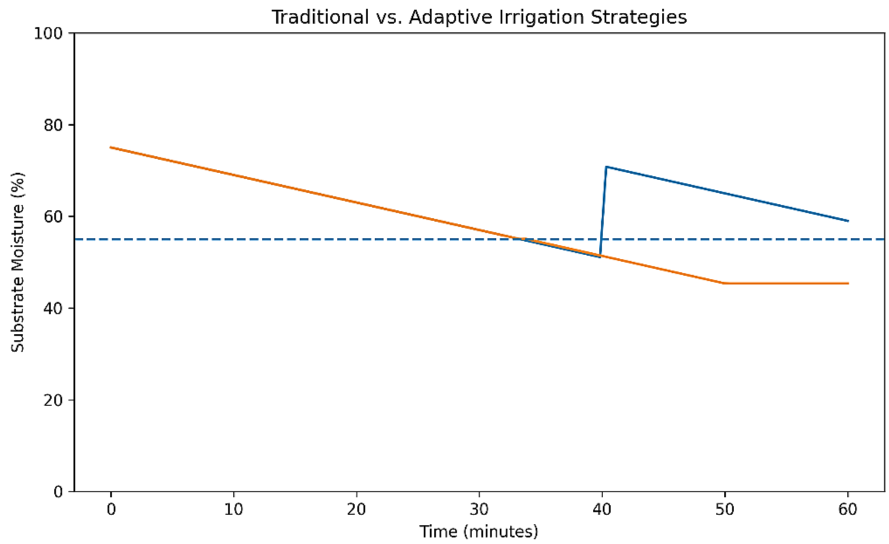
The proposed system was evaluated through functional simulation in Proteus Design Suite, reproducing the interaction between sensors, microcontroller, relay module, and equivalent loads representing pumps and solenoid valves. Under low-moisture conditions, the system consistently detected substrate values below the predefined threshold and triggered the activation of both the irrigation pump and the corresponding solenoid valve. This response occurred within milliseconds of threshold crossing, demonstrating the capability of the control logic to react in near real time to environmental changes. As shown in Figure 1, the adaptive control strategy enables a rapid recovery of substrate moisture toward the optimal operational range, followed by automatic deactivation once stability is restored, preventing prolonged water stress and unnecessary over-irrigation.

Figure 1. Adaptive Irrigation System Response under Substrate Moisture Decline.



When high-temperature conditions were emulated, the system correctly generated alarm signals and enabled the activation of mitigation outputs in extended configurations. Similarly, variations in luminosity were accurately detected by the BH1750 sensor, and the system responded according to the programmed rules. These results confirm the functional coherence of the multisensor control scheme and its capacity to integrate heterogeneous environmental variables within a unified decision framework. In contrast with conventional time-based irrigation, the comparative behavior illustrated in Figure 2 evidences that the adaptive strategy maintains substrate moisture within a narrower and more stable operational band, highlighting its superior responsiveness and efficiency under the rapid environmental fluctuations characteristic of warm and humid climates.

Figure 2. Comparison between Traditional Time-Based Irrigation and Adaptive Irrigation Control.



3.2. Robustness and Reliability Assessment

Simulation of fault scenarios revealed the importance of redundancy and verification mechanisms in agricultural automation. In cases of sensor malfunction or signal drift, the introduction of dual moisture sensors per sector enables cross-validation of readings, reducing the probability of false activations or missed irrigation events. The proposed integration of flow sensors provides an additional verification layer, ensuring that pump and valve activation corresponds to actual fluid movement. This approach transforms the system from a purely reactive controller into a self-monitoring architecture capable of detecting mechanical failures, obstructions, or hydraulic disconnections.

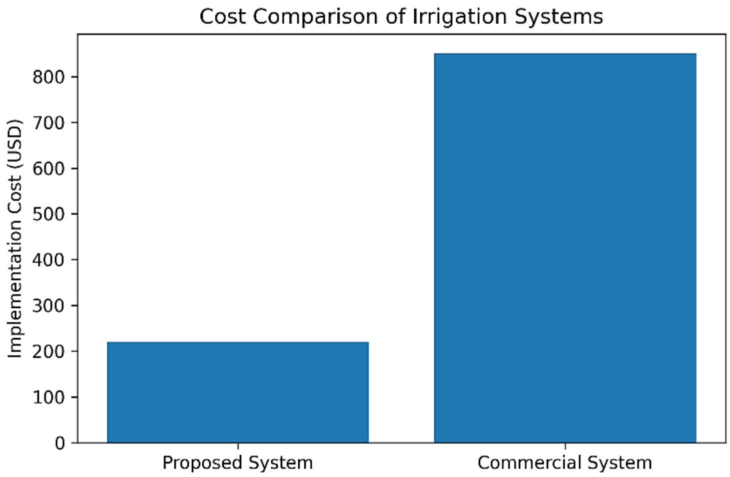
The inclusion of a watchdog timer demonstrated resilience against software lockups, ensuring automatic recovery without human intervention. In simulated power interruption scenarios, the proposed use of compact UPS units or battery backups preserved system continuity during critical thermal periods, a factor of particular relevance in tropical climates where short interruptions may lead to rapid plant stress.

3.3. Technical and Economic Implications

From a technical standpoint, the system exhibits high feasibility due to the use of widely available components, straightforward integration, and low computational requirements. The modular architecture allows the extension of the system to multiple irrigation zones without significant redesign, supporting scalability in both small and medium-sized greenhouses. Economically, the estimated implementation cost remains substantially below that of commercial automated irrigation systems, which frequently exceed USD 800. In contrast, the proposed configuration achieves comparable functional capabilities at a fraction of that cost, making it accessible to resource-constrained producers. As illustrated in Figure 3, this cost gap clearly demonstrates the economic viability of the proposed solution in comparison with market-available systems.

The low power consumption of the selected components further enhances sustainability, particularly when combined with the proposed integration of renewable energy sources. In warm and humid climates, where irrigation demand is continuous and energy infrastructure may be unstable, the combination of adaptive control and energy efficiency represents a critical advantage, positioning the system as a resilient and environmentally responsible alternative for tropical hydroponic production.

Figure 3. Comparison between Traditional Time-Based Irrigation and Adaptive Irrigation Control.



3.4. Discussion of the Proposed Contribution

The results highlight the effectiveness of an environmentally sensitive control strategy compared to conventional time-based irrigation schemes (Sharma et al., 2025). By linking irrigation events directly to real-time substrate moisture and contextual environmental variables, the system minimizes over-irrigation and mitigates water waste. Los sistemas de riego de precisión que utilizan monitoreo en tiempo real de la humedad del suelo y de las variables ambientales han demostrado mejorar la eficiencia en el uso del agua de riego al permitir decisiones basadas en datos, reduciendo así la sobreirrigación y el desperdicio de agua (Abdelmoneim et al., 2025). This approach is especially relevant in tropical regions, where high evaporation rates and thermal variability render fixed schedules ineficiente (Nikolaou et al., 2020).

Unlike generic commercial solutions designed for temperate environments, the proposed system explicitly addresses the operational challenges of warm and humid climates (Hopwood et al., 2024). Its multisensor architecture enables a dynamic response to microclimatic fluctuations, stabilizing the root-zone environment and improving the physiological conditions of hydroponic crops. Integrated multi-sensor monitoring and intelligent control mechanisms have been shown to improve environmental management in greenhouse environments by capturing and processing diverse real-time data streams, enabling dynamic responses to microclimatic fluctuations that support plant growth and resource efficiency (Bicamumakuba et al., 2025).

The combination of low cost, adaptability, and robustness positions the system as a viable technological alternative for sustainable agriculture in regions such as Manabí. Digital and IoT-based irrigation solutions have been recognized for enhancing water management efficiency while offering scalable and potentially cost-effective deployment for diverse agricultural contexts (Parra-López, 2025). Overall, the findings demonstrate that the integration of low-cost sensing, adaptive control logic, and modular hardware can yield a technically robust and economically viable irrigation solution, capable of improving resource efficiency and production stability in hydroponic greenhouses under tropical conditions. Precision irrigation water-saving technologies, including low-cost sensor networks and automated control, significantly enhance water use efficiency and sustainability in agricultural systems (Lakhiar et al., 2024).

IV. CONCLUSION

This study presented the design and validation of an adaptive automated irrigation system for hydroponic greenhouses operating under warm and humid climatic conditions, with specific applicability to the coastal region of Manabí, Ecuador. The proposed architecture integrates multisensor monitoring, microcontroller-based decision logic, and modular actuation, enabling real-time adjustment of irrigation according to substrate moisture and environmental variables. Simulation results demonstrated that the system responds promptly to critical moisture thresholds, stabilizes root-zone conditions, and avoids prolonged water stress, outperforming conventional time-based irrigation schemes.

From a technical perspective, the system exhibits high feasibility due to its simple integration, low computational demand, and compatibility with widely available electronic components. The incorporation of redundancy mechanisms, flow verification, watchdog recovery, and energy backup transforms the controller into a self-supervised and resilient platform capable of maintaining operational continuity under sensor faults, software disruptions, and power instability—conditions frequently encountered in tropical agricultural environments.

Economically, the proposed solution achieves comparable functional capabilities to commercial automated irrigation systems at a substantially lower implementation cost, enhancing its accessibility for small and medium-sized producers. In combination with its low energy consumption and potential integration with renewable energy sources, the system represents a scalable and sustainable alternative for hydroponic production in regions characterized by high thermal variability and limited technological infrastructure.

Overall, the findings confirm that low-cost adaptive control strategies can significantly improve water-use efficiency, environmental stability, and production reliability in hydroponic greenhouses under tropical conditions. Future work will focus on experimental field deployment, long-term performance evaluation, and the integration of predictive control algorithms based on climatic forecasting and machine learning techniques.

CONFLICT OF INTEREST

There is no conflict to disclose.

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