



Automated Hydroponic System: Demonstrating Robustness in Panama City's Uncontrolled Climate Conditions

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Received: 13 02 2025; Accepted: 12 05 2025

Available: 30 04 2026

Abstract: Traditional agriculture faces growing challenges such as water scarcity, soil degradation, and the increasing demand for sustainable food production. Hydroponics offers an innovative solution, enabling soil-free cultivation of plants through nutrient-rich water systems, optimizing resource use and ensuring controlled growth conditions. This project focuses on the development and implementation of an automated hydroponic system for lettuce cultivation, designed to perform under the challenging environmental conditions of Panama's humid and hot climate. The system integrates advanced sensor technologies, programmable controllers, and a digital twin for real-time monitoring and management of critical variables, including pH, electrical conductivity (EC), temperature, and nutrient concentrations. A user-friendly interface facilitates data visualization and manual adjustments when necessary. The implementation process addressed technical challenges such as sensor calibration, hardware-software integration,

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Peer Review under the responsibility of Universidad Nacional Autónoma de México.

and the development of efficient control algorithms. Experimental results demonstrated the system's robustness and adaptability, achieving significant improvements in plant growth consistency and health. The automated features reduced resource consumption, minimized human intervention, and maintained optimal growth conditions despite environmental stressors. These outcomes validate the viability of automation in hydroponic systems and highlight its potential for advancing sustainable and urban agriculture in tropical regions.

Keywords: Hydroponics, automated systems, sensor calibration, tropical agriculture, robust design.

1. Introduction

Agriculture in tropical climates presents a unique set of challenges that can hinder sustainable food production. High humidity, elevated temperatures, and variable rainfall patterns make it difficult to maintain stable growing conditions for crops. These environmental factors also promote the proliferation of pests and diseases, increasing the need for chemical interventions that can degrade soil quality over time. Soil degradation, a result of deforestation, over-cultivation, and improper agricultural practices, is a growing concern, leaving many regions with limited fertile land.

1.1 Problem Statement

Water availability is another critical issue. While tropical regions may experience heavy rainfall, water resources are often unevenly distributed and can become polluted. This makes consistent access to clean water a pressing challenge, especially for agriculture, which is one of the largest consumers of this resource. The demand for food production continues to grow, driven by expanding urban populations, while the availability of arable land decreases due to urbanization and other factors.

Hydroponics offers a practical alternative to traditional soil-based agriculture. By using a soil-free system that delivers nutrients through water, hydroponics significantly reduces dependence on fertile land and optimizes resource usage. The controlled environment of hydroponic systems allows growers to manage factors like pH, nutrient levels, and temperature with precision, mitigating many of the uncertainties posed by external conditions (Pache et al., 2022).

This project explores the development of an automated hydroponic system tailored to the tropical environment of Panama. With the integration of sensors,

controllers, and user-friendly software, the system aims to provide consistent growing conditions for lettuce cultivation. By focusing on automation and monitoring, the project seeks to address key challenges such as resource efficiency, crop reliability, and adaptability to humid, hot climates. (Chaiwongsai, 2019)

While hydroponics is not a universal solution to all agricultural challenges, its potential to supplement traditional farming in regions with limited resources or challenging environmental conditions makes it an area of increasing relevance (Avercheva et al., 2009; Mendon and Bavya, 2022; Richa et al., 2021; Rico, 2019; Sahu et al., 2024). This project contributes to the ongoing exploration of hydroponics as a sustainable agricultural practice, with a focus on robustness and efficiency in tropical climates.

1.2 Project Context

Panama, located in Central America, is characterized by a tropical climate with high humidity, consistently warm temperatures, and distinct rainy and dry seasons. These climatic conditions present several challenges for agricultural production. The high humidity levels, while beneficial for some crops, can create an environment conducive to pests, fungi, and other diseases that affect plant health. Similarly, elevated temperatures can cause water loss through evaporation, adding to the stress on water resources. During the dry season, access to water becomes a critical concern, further complicating agricultural efforts.

The limited availability of arable land near urban centers adds another layer of complexity. Rapid urbanization has pushed farming activities to more distant regions, increasing the cost and reducing the efficiency of food distribution. This is particularly relevant in areas like Panama City, where population growth and urban sprawl have intensified these challenges.

In this context, automation in hydroponic systems emerges as a promising approach to address these issues. By leveraging sensors and programmable controllers, automated hydroponic systems offer precise control over critical growing parameters such as pH, electrical conductivity (EC), and temperature. These systems can optimize water and nutrient use, reducing waste and ensuring that plants receive consistent care irrespective of external environmental fluctuations.

Automation also minimizes the need for constant human intervention, making the system more efficient and reducing the risk of human error. This capability is particularly advantageous in regions like Panama, where climatic variability can demand frequent adjustments to traditional farming practices. Furthermore, integrating real-time monitoring systems allows growers to respond promptly to any deviations, enhancing the reliability and resilience of the production process.

The project outlined in this paper was conducted to develop an automated hydroponic system adapted to the specific climatic challenges of Panama. Focusing on lettuce cultivation, the system combines automation technologies with local environmental considerations to create a robust solution for sustainable agriculture. By emphasizing automation, the project not only seeks to improve the efficiency of hydroponic systems but also explores their potential as a viable agricultural alternative in tropical climates.

1.3 Objectives

The primary objective of this project is to develop and test a robust hydroponic system tailored to the tropical climate of Panama. This involves designing a system capable of maintaining consistent and optimal growing conditions for lettuce cultivation despite the high humidity and elevated temperatures characteristic of the region. The system aims to address key challenges such as water and nutrient management, as well as environmental stability, which are critical for successful hydroponic farming in challenging climates.

To achieve this goal, the project integrates advanced sensors, actuators, and digital monitoring tools to ensure precise measurement and control of critical parameters, including pH levels, electrical conductivity (EC), temperature, and humidity. The system's automation is designed to reduce human intervention, improve efficiency, and provide real-time feedback to users through a user-friendly interface.

The specific objectives include:

- Designing a sensor network: To measure key variables such as pH, EC, temperature, and humidity with accuracy and reliability (Kulkarni et al., 2024).
- Developing a control system: To automate the adjustment of water and nutrient levels based on real-time sensor data.
- Creating a digital monitoring tool: To provide users with a visual interface for monitoring and adjusting system parameters.
- Testing system performance: To evaluate the system's ability to maintain optimal conditions and support healthy lettuce growth under the environmental stressors typical of tropical climates.

By focusing on these objectives, the project contributes to the advancement of automated hydroponic systems as a sustainable agricultural practice (Munandar et al., 2018; Perwiratama et al., 2019; Tatas et al., 2022; Thakur et al., 2023; Yaqin et al., 2022) the development of technology in the area of IT leads to the appearance of technology called the Internet of Things (IoT). It aims to demonstrate the feasibility and benefits of integrating technology into agriculture, particularly in regions facing unique environmental challenges.

2. Materials and Methods

The hydroponic system developed in this project is designed with a focus on robustness and efficiency, tailored to operate effectively in Panama's humid and hot tropical climate. The system integrates structural and functional components to support the growth of lettuce in a controlled environment while addressing challenges associated with tropical agriculture.

Structural components: The hydroponic system's structure is composed of readily available and cost-effective materials, ensuring accessibility and sustainability. Key components include:

- PVC pipes:
 - Function: Serve as the primary conduit for delivering nutrient-rich water to the plant roots.
 - Design: Thick, durable PVC pipes with evenly spaced holes to hold the plant baskets. The pipes are arranged with a slight incline (~5 cm) to ensure a steady flow of the nutrient solution via gravity.
 - Optimization: The pipes were coated with a light-blocking material to prevent algae growth, which is common in high-humidity environments.

- Wooden frame:**
 Function: Provides a stable and supportive base for the PVC pipe system.
 Design: Constructed from treated wood to ensure durability against moisture and the weight of the system. The frame is designed to hold the pipes at an optimal angle for nutrient flow.
 Adjustments: Additional supports were incorporated to counteract any potential warping due to prolonged exposure to humidity.
- Water reservoir:**
 Function: Acts as a storage unit for the nutrient solution.
 Design: A tank covered with a black plastic bag to protect the nutrient solution from heat and sunlight exposure. A submersible pump within the reservoir ensures continuous circulation.
- Plant baskets and growing medium:**
 Function: Secure the lettuce plants and facilitate root access to the nutrient solution.

Design: Small, reusable plastic baskets filled with a combination of coconut fiber and a sponge-like medium to provide stability and moisture retention.

System Layout: The system follows a Nutrient Film Technique (NFT) configuration, where a thin film of nutrient-rich water flows through the PVC pipes, continuously bathing the roots of the plants. This technique ensures efficient nutrient delivery while minimizing water usage.

- Arrangement:** The pipes are connected in a closed-loop system. The nutrient solution is pumped from the reservoir to the highest point of the pipe array and flows back into the reservoir after passing through the plants.
- Compact design:** The system is built horizontally, but being extremely narrow, it can have multiple layers vertically to maximize space efficiency, making it suitable for urban farming or areas with limited land availability.

Different perspectives of the system are shown in Figure 1.

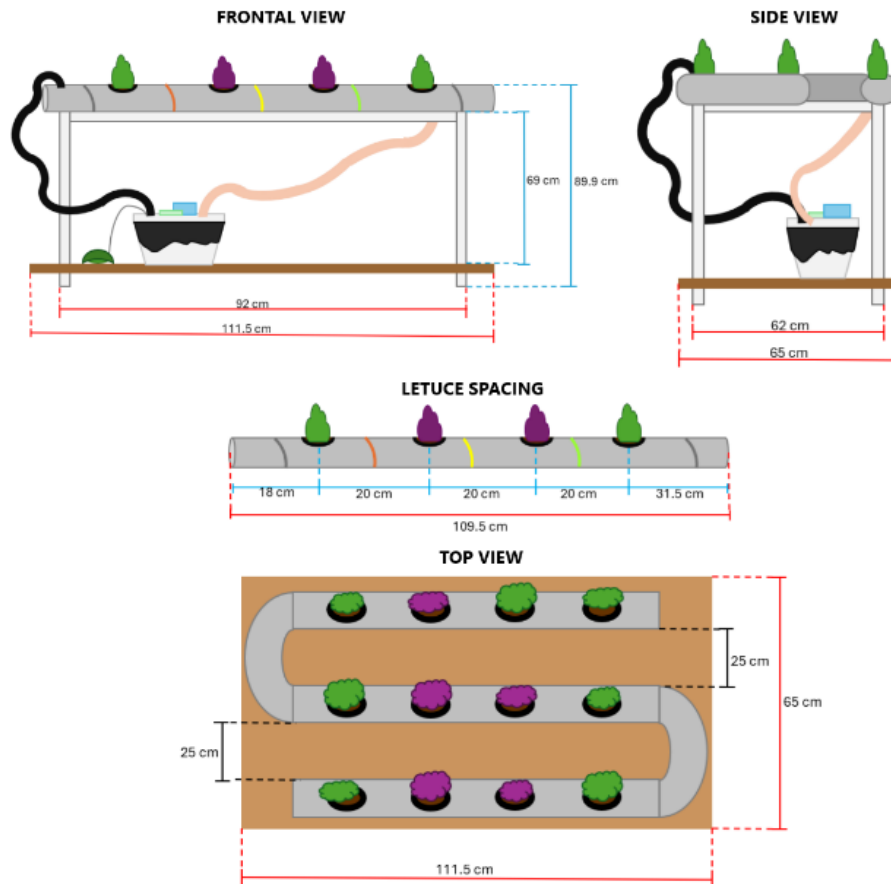


Figure 1. Schematic views of the PVC tube configuration.

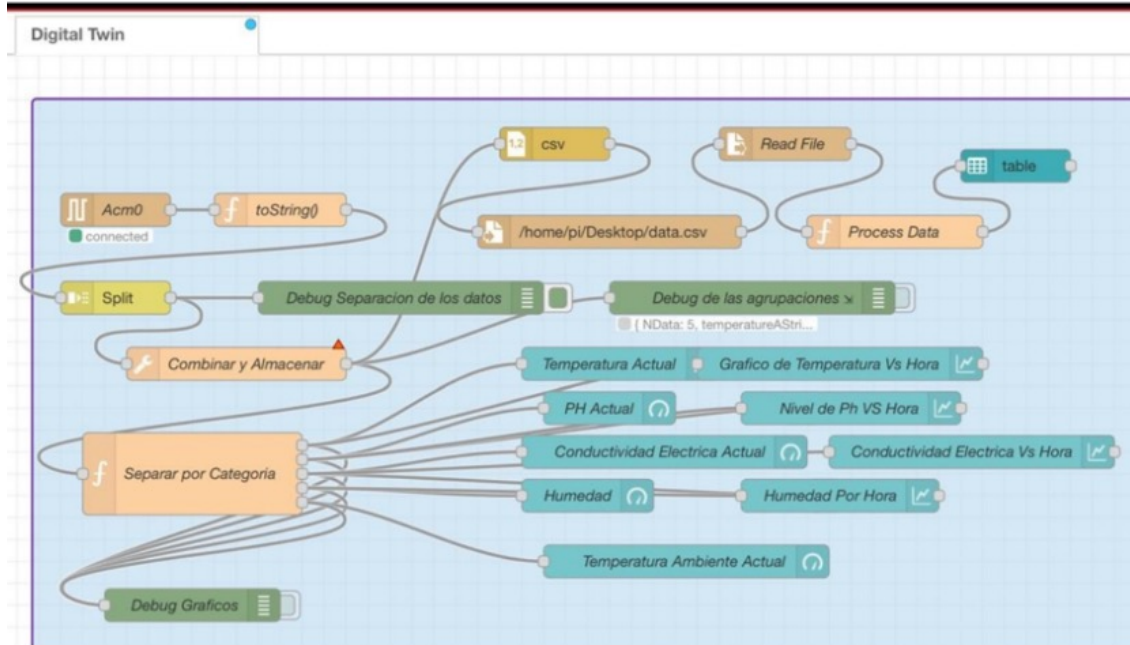


Figure 2. Node-RED interface.

2.2 Key Features

The hydroponic system incorporates several advanced automation technologies and sensor integrations to ensure precise control and monitoring of the growing conditions. These features collectively enhance the system's efficiency, reliability, and adaptability, particularly in the challenging tropical environment of Panama.

a. Automation technologies:

- Digital twin concept: The system employs a digital twin model to provide real-time monitoring and simulation of the physical system. This virtual representation collects data from sensors and reflects the state of the hydroponic setup, enabling users to make informed adjustments to optimize plant growth conditions.
- Node-RED: Node-RED, an open-source programming tool, was utilized to develop a user-friendly interface for monitoring and controlling the system. This platform facilitates communication between sensors and actuators while allowing users to visualize real-time data through dashboards, see Figure 2.
- Key functions include logging sensor readings, alerting users to parameter deviations, and providing a platform for manual control when needed.
- Arduino: The central control of the system is managed by Arduino microcontrollers. These devices process data from sensors and trigger actuators to

maintain optimal conditions within the system. The Arduino units also ensure reliable communication between the hardware components and the Digital twin via the I2C protocol.

b. Sensor setup:

- pH monitoring: A pH sensor is installed to measure the acidity or alkalinity of the nutrient solution, as seen in Figure 3. Maintaining a pH range of 5.5 to 6.5 is critical for nutrient absorption by plants. The sensor's calibration data ensures accurate and consistent readings.

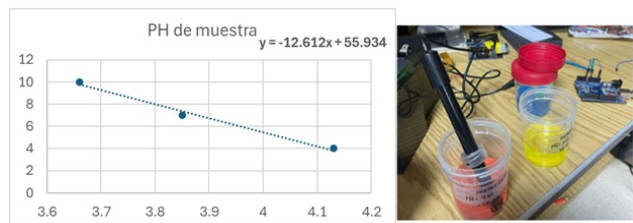


Figure 3. pH calibration data obtained can be seen. Different voltages can be obtained (Y-axis) at different pH levels (X-axis).

- Electrical conductivity (EC) monitoring: The EC sensor measures the nutrient concentration in the water

(Jamil et al., 2023) such as Total Dissolved Solids (TDS). This data helps in maintaining the appropriate nutrient levels to support healthy plant growth. Adjustments to the solution are automated based on EC readings. The wiring diagram can be seen in Figure 4.

- **Temperature monitoring:**
A DS18B20 temperature sensor is utilized to monitor the water temperature, ensuring it remains within an optimal range for lettuce cultivation. An additional DHT11 sensor tracks ambient temperature and humidity, providing insights into environmental conditions. Both can be seen in Figure 5.

- **Humidity monitoring:**
Humidity levels are monitored using the DHT11 sensor to assess environmental conditions that could affect plant health and system performance.

Figure 6 provides a block diagram representation of the system's core components and their interconnections from a control perspective.

Figure 7 provides a schematic drawing of the wiring required for the hydroponic system.

2.3 Environmental Adaptations

The hydroponic system was designed with several adaptations to address the high humidity and elevated temperatures characteristic of Panama's tropical climate. These modifications aim to ensure the system's stability and maintain optimal conditions for lettuce growth under challenging environmental conditions (Avercheva et al., 2009; Mujtahidin et al., 2024).

- **Shaded mesh:**
Purpose: To reduce the intensity of direct sunlight, preventing excessive heating of the nutrient solution and plant roots.
Implementation: A shaded mesh was installed above the system to diffuse sunlight while still allowing sufficient light penetration for photosynthesis. This setup helps to stabilize internal temperatures and protect the plants from thermal stress.
- **Improved ventilation:**
Purpose: To manage humidity levels and prevent the buildup of moisture that can lead to fungal growth on plants.
Implementation: Fans or natural ventilation openings were incorporated into the system's environment to

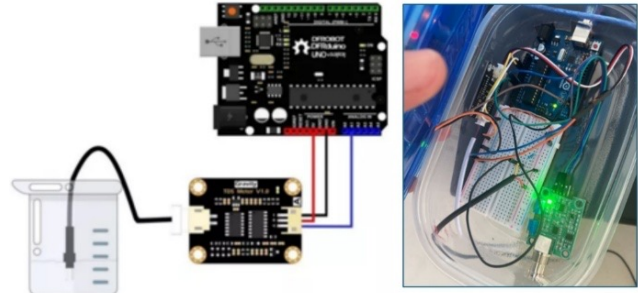


Figure 4. EC sensor wiring diagram (left) and the physical implementation (right).

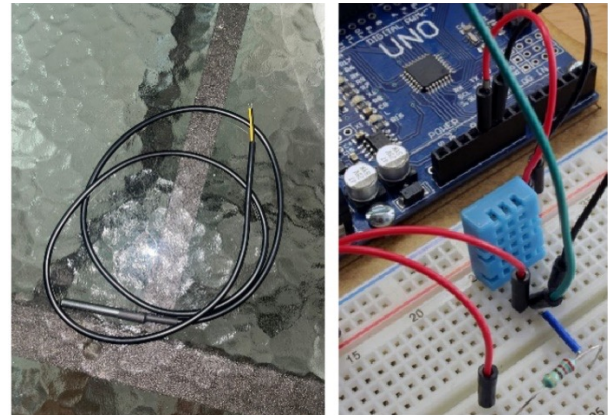


Figure 5. DS18B20 sensor (left) and DHT11 sensor (right).

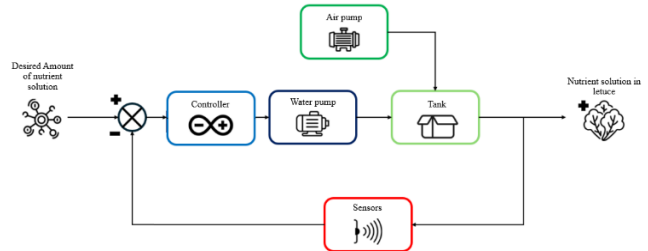


Figure 6. Control block diagram representation of the system.

promote airflow around the plants and structure. This adjustment minimizes stagnant air pockets and reduces the risk of diseases caused by high humidity.

- **Protective coverings:**
Purpose: To shield critical system components from environmental stressors like sunlight and rain.
Implementation: The PVC pipes were wrapped in light-blocking material to prevent algae growth inside the conduits. Additionally, the water reservoir was

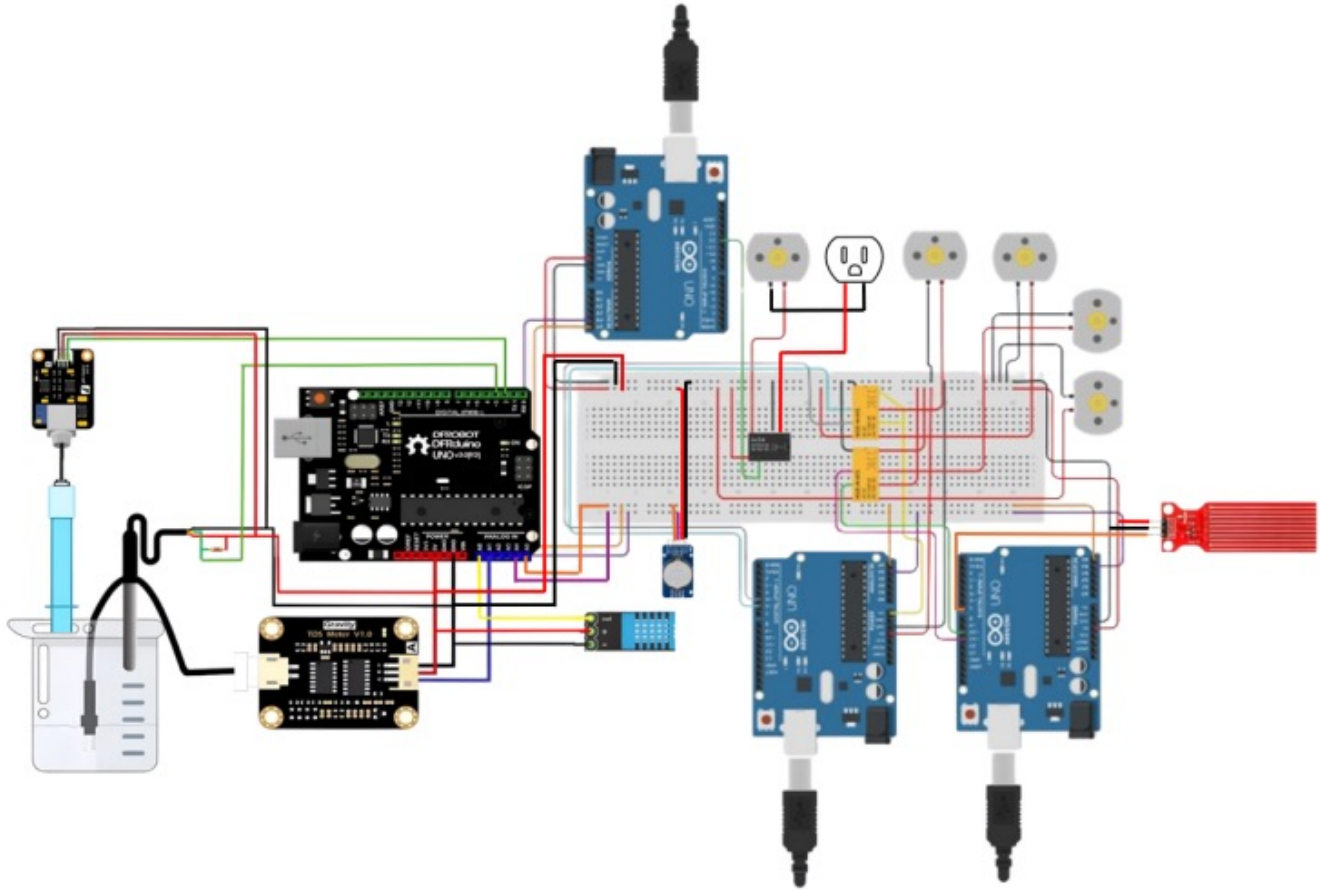


Figure 7. Hydroponic system wiring schematic.

covered with black plastic bags to reduce the effects of sunlight, such as overheating and evaporation, which could alter the composition of the nutrient solution (see Figure 8).

in natural cooling and humidity management. The slight incline of the PVC pipes also ensures proper drainage and prevents water stagnation, reducing the risk of fungal infections.



Figure 8. PVC pipe cover (left and middle) and tank wrapping (right).

- System layout adjustments:
 Purpose: To optimize the system’s overall performance under environmental stressors.
 Implementation: The horizontal arrangement of the system maximizes airflow between the plants, aiding

3. Results

The hydroponic system’s development involved the integration of carefully chosen components to create a functional and efficient setup tailored to Panama’s tropical climate. Each component was selected based on its compatibility, durability, and ability to perform in humid and high-temperature environments, while assembly and calibration ensured optimal system performance.

3.1 System Development

Central to the system’s operation was a 10-watt submersible water pump with a flow rate of 160 gallons per hour (GPH). The pump’s capacity was selected to maintain a consistent flow of nutrient-rich water across the system’s PVC pipe network. A flow control valve allowed for precise

adjustments, ensuring the water film adequately bathed the roots without causing flooding. Complementing the water pump, an air pump capable of delivering 4 liters per minute oxygenated the nutrient solution in the reservoir. This prevented root hypoxia, a common issue in hydroponic systems, and ensured robust plant growth.

The reservoir, with an approximate volume of 41.63 liters, was covered with black plastic to protect it from sunlight. This measure minimized algae growth and reduced the risk of overheating, which could compromise the nutrient solution's quality. The structural components, including the PVC pipes and treated wooden frames, were designed to withstand prolonged exposure to high humidity. The PVC pipes were coated with a light-blocking material to further inhibit algae growth and were arranged at a 5 cm incline to facilitate effective water flow and drainage.

Sensor integration was a critical aspect of the system's functionality. A pH sensor, calibrated using buffer solutions, provided real-time monitoring of the nutrient solution's acidity, while an electrical conductivity (EC) sensor ensured nutrient concentrations remained within the optimal range. Water and ambient temperatures were monitored using DS18B20 and DHT11 sensors, respectively, with placement optimized for accuracy. The sensors were calibrated to ensure precision, with pH sensor accuracy confirmed using a laboratory-grade reference and EC calibration reducing the margin of error to approximately 5%.

The assembly process began with constructing the wooden frame to securely support the PVC pipes and reservoir. Each component was meticulously aligned to ensure structural stability and functionality. Initial system testing revealed opportunities for refinement, such as adjusting the pump flow rate and ensuring all electrical connections were well-insulated to prevent short circuits in the humid environment. The structure can be seen in Figure 9.

Calibration played a pivotal role in system optimization. The sensors were rigorously tested and adjusted to ensure reliable data collection. For example, pH sensors were calibrated with solutions of known pH values, while EC sensors were validated with nutrient solutions of standard conductivity. These calibration processes enabled precise monitoring, which is essential for maintaining the ideal growing conditions for lettuce.

Throughout the development phase, iterative testing allowed the team to address challenges such as overheating in the reservoir and variability in water flow. Adjustments included enhancing the protective measures



Figure 9. Finished structure.

for electronic components and refining the nutrient flow system to maximize resource efficiency.

This thorough and methodical approach to system development ensured a robust setup capable of maintaining optimal growing conditions, even under the challenging environmental conditions of Panama's tropical climate.

3.2 Experimental Setup

The experimental setup was designed to test the hydroponic system's performance under the natural environmental conditions of Panama City, with its characteristic tropical climate. The testing location exposed the system to ambient temperatures ranging from 28°C to 34°C and humidity levels that fluctuated between 70% and 95%. These conditions were monitored in real-time using the integrated DHT11 sensor, providing a constant stream of data on temperature and humidity. To mitigate environmental stressors, the shaded mesh and black plastic coverings for the reservoir were evaluated for their effectiveness in stabilizing internal conditions, particularly the nutrient solution temperature, which was maintained within

an optimal range of 20°C to 25°C for lettuce cultivation. Ventilation measures and the system's structural layout were similarly tested for their contribution to airflow and overall environmental control.

Before introducing the plants, the system underwent a calibration process to ensure all sensors and pumps operated within specified ranges. The pH and EC sensors were calibrated to maintain nutrient levels between pH 5.5 and 6.5 and EC 1.5 to 2.5 mS/cm. Following calibration, lettuce seedlings were transplanted into the hydroponic system's baskets, ensuring even spacing to promote uniform growth. The plants' roots were immersed in the flowing nutrient solution, which was continuously circulated by the submersible pump and oxygenated by the air pump.

Throughout a four-week growth period, the system's performance was continuously monitored. Real-time data, including pH, EC, temperature, and humidity readings, were visualized through the digital twin interface. This interface allowed researchers to identify trends and make necessary adjustments. Weekly measurements of plant growth, including height, leaf count, and overall health, were recorded to evaluate the system's impact on cultivation.

In addition to regular monitoring, controlled stress tests were introduced. These included deliberate increases in the nutrient solution temperature and variations in the EC levels to simulate real-world challenges such as heatwaves or nutrient imbalances. The system's ability to detect these changes and respond effectively through its automated controls was a key focus of the evaluation.

At the conclusion of the testing period, the lettuce plants were harvested, and their biomass was measured. These results provided a quantitative basis for assessing the system's effectiveness in supporting healthy plant growth. Observations highlighted the significant role of the shaded mesh in preventing overheating and maintaining stable conditions in the reservoir. Additionally, the airflow generated by the ventilation setup reduced the risk of fungal growth, even under high humidity. The accuracy of the sensors was critical in detecting deviations and enabling timely corrective actions, which ensured the stability of the growing environment throughout the test period.

This experimental setup provided a rigorous assessment of the hydroponic system's ability to adapt to the challenging environmental conditions of Panama City. The insights gained from this testing highlight the robustness and reliability of the system in maintaining optimal conditions for lettuce cultivation.

3.3 Data Collection

Data collection was a critical aspect of the experiment, aimed at assessing the hydroponic system's performance and its ability to maintain optimal conditions for lettuce growth. A combination of automated and manual methods was employed to ensure accuracy and reliability, with key metrics such as sensor readings, nutrient levels, plant growth rates, and final yield being the focal points of analysis.

The system's sensors played a pivotal role in monitoring environmental and nutrient conditions throughout the experiment. Real-time data on pH, electrical conductivity (EC), water temperature, and ambient humidity were logged continuously using the digital twin interface, which provided a clear visualization of trends and deviations. For instance, pH levels were closely tracked to remain within the optimal range of 5.5 to 6.5. This was validated through calibration processes and periodic comparisons with manual pH meter readings. The consistency of EC readings, maintained between 1.5 and 2.5 mS/cm, was similarly verified, ensuring the nutrient solution was adequate for healthy plant growth. Any minor fluctuations in these metrics were automatically adjusted by the system, showcasing its responsiveness to real-time data.

Plant growth data was collected weekly to evaluate the system's impact on lettuce development. Measurements included plant height, leaf count, and visual health assessments. These metrics provided insight into the uniformity of growth across the system, revealing a strong correlation between consistent sensor readings and healthy plant development. Additionally, growth differences between plants positioned in different parts of the system were analyzed to account for potential variations in light exposure or nutrient flow. This detailed data allowed the identification of subtle discrepancies in system performance, which were addressed during the testing phase.

At the end of the four-week growth period, the lettuce plants were harvested, and their biomass was measured. This final yield provided a quantitative basis for evaluating the system's effectiveness. Each plant was weighed and compared against expected benchmarks for hydroponically grown lettuce, with results confirming the system's ability to support robust growth under tropical environmental conditions. The comparison of pre- and post-harvest plant sizes highlighted the efficiency of nutrient utilization and the uniformity of conditions provided by the system.

The integration of automated data logging through the digital twin significantly enhanced the data collection process, reducing human error and ensuring uninterrupted monitoring. The Node-RED dashboard, which displayed real-time sensor readings and historical data trends, enabled the research team to identify and address anomalies promptly. For example, during a brief spike in ambient temperature, the system adjusted nutrient solution flow rates and aeration to maintain stability, a process fully documented in the data logs.

By systematically collecting and analyzing these metrics, the experiment demonstrated the hydroponic system's capability to maintain optimal conditions and support consistent lettuce growth. This comprehensive dataset provided the foundation for understanding the system's performance and identifying areas for potential refinement, ensuring the success of the experimental objectives.

4. Results

The hydroponic system demonstrated robust adaptability and reliable operation under the challenging environmental conditions of Panama City. Over the course of several weeks, it maintained stable performance despite fluctuations in ambient temperature and humidity, validating its design and calibration processes.

4.1 System Performance

The system's adaptability was most evident during periods of increased environmental stress, such as elevated daytime temperatures and high humidity levels. These conditions posed potential risks to the nutrient solution's temperature and the system's overall stability. However, the automated controls effectively adjusted flow rates and aeration levels to mitigate these risks. For example, the submersible pump's adjustable flow control ensured that the nutrient solution circulated efficiently, maintaining consistent hydration and nutrient delivery to the plants even under varying environmental loads.

Calibration precision played a crucial role in ensuring the accuracy of the system's sensors, which monitored key parameters such as pH, electrical conductivity (EC), and temperature. The pH sensor was calibrated using standard buffer solutions with known values of pH 4.0 and 7.0, resulting in an error margin of approximately ± 0.5 . Similarly, the EC sensor was calibrated using reference solutions of predetermined conductivity, achieving a margin of error between 5% and 7%. These calibration efforts were validated through periodic cross-referencing

with manual measurements, confirming the reliability of sensor outputs over time.

The reliability of the sensors was further evidenced by their consistent performance during real-time monitoring. The Digital Twin interface provided a clear visualization of sensor data, allowing the research team to track trends and identify anomalies promptly. For example, a brief deviation in pH levels caused by a temporary fluctuation in nutrient composition was quickly detected and corrected by the system's automated adjustments. This responsiveness underscored the system's ability to maintain stable conditions with minimal human intervention.

Despite these successes, some minor challenges were observed. Sensor readings occasionally showed slight drift after prolonged operation, necessitating recalibration to ensure continued accuracy. This drift was addressed through routine maintenance and recalibration protocols, which were integrated into the system's workflow to minimize disruptions.

Overall, the system's performance highlighted its resilience and precision in adapting to environmental changes and maintaining optimal conditions for plant growth. The combination of reliable sensors, precise calibration, and automated adjustments enabled the system to operate effectively in a challenging tropical environment, establishing a strong foundation for further refinement and scaling.

4.2 Plant Growth and Yield

The experimental trials demonstrated the effectiveness of the automated hydroponic system in supporting healthy lettuce growth under tropical conditions. Growth metrics, including plant height, leaf count, and visual health assessments, were recorded regularly throughout the four-week period, providing detailed insights into plant development. The data revealed consistent growth across the system, with most plants exhibiting uniform size and health by the end of the trial. Early measurements showed steady increases in height and leaf number, which accelerated as plants neared the harvesting stage, underscoring the system's ability to maintain optimal growing conditions. This growth can be seen in Figure 10.

Yield was assessed by comparing pre- and post-harvest biomass, see Figure 11. Each plant was weighed immediately before transplantation into the system and again at the end of the trial. The results indicated substantial biomass accumulation, with final weights aligning closely with benchmarks for hydroponically grown lettuce.

Notably, plants in the automated system showed higher consistency in size and weight compared to traditional setups, which often exhibit variability due to uneven nutrient distribution and environmental fluctuations.

When compared to traditional soil-based farming methods, the hydroponic system demonstrated clear advantages in terms of resource efficiency and uniformity of results. Traditional methods often require significantly more water and nutrients, with lower yield predictability due to external factors such as soil quality and weather conditions. By contrast, the hydroponic system minimized resource usage through precise control of nutrient delivery and water recycling. Furthermore, the consistent airflow and shading provided by the system mitigated the risks of fungal growth, a common issue in high-humidity environments, thereby improving overall plant health.

The system's performance in promoting growth and maximizing yield highlights its potential for scaling as an alternative to traditional farming in tropical regions. While minor challenges, such as occasional fungal outbreaks, were observed, these were effectively managed through timely interventions. The results reinforce the system's capability to produce high-quality lettuce efficiently and sustainably under challenging environmental conditions.

The data collected throughout an entire month can be seen in Table 1.

This data confirms substantial leaf size growth as shown in Figure 12.

4.3 Energy and Resource Efficiency

The hydroponic system demonstrated significant energy and resource efficiency, a critical advantage in its design for sustainable agriculture. By optimizing energy consumption, minimizing water usage, and carefully managing nutrient delivery, the system proved its capability to operate with reduced environmental impact compared to traditional farming methods.

Energy consumption was carefully monitored throughout the system's operation. The transition from a 10-watt submersible pump to a programmable micro pump played a pivotal role in reducing unnecessary energy usage. The micro pump's ability to precisely control water flow meant that energy was only expended when necessary, avoiding continuous operation during periods of inactivity. Additionally, the air pump, rated at 4 liters per minute, provided sufficient oxygenation for the nutrient solution without excessive energy demands. Together, these components ensured that the system achieved a balance between functionality and energy efficiency.



Figure 10. Plant development.



Figure 11. Plant state. Pre harvest (left) and post-harvest (right).



Figure 12. Growth rate plot.

Table 1. Growth rate summary.

.....									
Day	Section	Row	# Leafes	Size (Inches)	Section	Row	# Leafes	Size (Inches)	
.....	1	11	3	....	1	7	2	
		2	11	3		2	4	2	
		3	8	3		3	20	2	
	1	7	1.5	1	9	2
			2	7	1.5		2	4	2
			3	8	1.5		3	8	2
.....	1	16	3.5	....	1	9	4.5	
		2	13	4		2	9	3	
		3	13	3		3	26	4.5	
	1	8	3	1	15	4.5
			2	9	3		2	6	3.5
			3	9	4.5		3	4	4
.....	1	18	5.25	....	1	12	6.5	
		2	15	5.75		2	11	4.5	
		3	18	5.5		3	25	6.5	
	1	10	5.25	1	15	5
			2	9	6		2	10	5.5
			3	12	7		3	12	5.75
.....	1	-	5.5	....	1	-	8.25	
		2	-	5.5		2	-	5.25	
		3	-	5.5		3	-	6.5	
	1	-	7	1	-	6.5
			2	-	6		2	-	5.5
			3	-	8		3	-	7.5

Water usage was another area where the system excelled. The recirculation mechanism minimized waste by reusing the nutrient solution, a key feature of the Nutrient Film Technique (NFT) employed in the system. By maintaining a thin and continuous film of water over the roots, the NFT design ensured that plants received adequate hydration without the need for excessive water volumes. This approach significantly reduced water consumption compared to traditional soil-based farming, where water loss through evaporation and runoff is common. The system's ability to recycle water made it highly efficient in a tropical environment where water conservation is a priority.

Nutrient optimization was achieved through regular monitoring of pH and electrical conductivity (EC) levels. Real-time sensor data allowed for precise adjustments to the nutrient solution, ensuring that plants received

only what they needed for healthy growth. This prevented overuse of fertilizers and avoided nutrient imbalances that could otherwise lead to waste or poor plant performance. The consistency of pH and EC levels over time demonstrated the effectiveness of the system's automated controls in maintaining optimal conditions. This approach not only improved resource efficiency but also minimized the environmental impact associated with excess nutrient runoff.

The system's efficiency in energy use, water conservation, and nutrient management highlights its potential as a sustainable alternative to traditional agricultural methods. By leveraging precise control mechanisms and a closed-loop design, the hydroponic setup exemplifies a resource-efficient approach to urban and tropical farming challenges.

5. Conclusions

The automated hydroponic system demonstrated remarkable effectiveness in addressing the challenges of tropical agriculture. Designed to operate under Panama's humid and hot climate, the system showcased its ability to maintain optimal growing conditions for lettuce cultivation through precise control of environmental and nutrient parameters. Over the four-week experimental period, consistent plant growth and high yields were achieved, validating the robustness and reliability of the system's design.

By integrating automation technologies, such as real-time monitoring via the digital twin interface, the system proved capable of adapting to environmental stressors with minimal human intervention.

Key strengths of the system included its efficient use of resources and the precision with which it maintained growing conditions. The closed-loop design optimized water use, significantly reducing waste compared to traditional soil-based methods. Similarly, the automation of nutrient delivery and environmental controls minimized overuse of fertilizers and ensured consistent pH and electrical conductivity levels. Energy efficiency was another standout feature, with the programmable micro pump and air pump operating effectively while consuming minimal power. These innovations highlight the system's potential for sustainable agricultural applications in regions facing water scarcity, high temperatures, or limited arable land.

While the system performed well overall, some challenges were encountered during testing. Sensor drift, particularly in pH and EC readings, required periodic recalibration to maintain accuracy. Environmental factors, such as high humidity, occasionally led to fungal growth on plants, necessitating interventions like improved airflow and fungicide applications.

These issues underscore areas for improvement in the system's design, such as enhancing sensor durability and refining methods for humidity control. Despite these challenges, the system's ability to detect and respond to anomalies through automated controls demonstrated its reliability in managing dynamic conditions.

The findings from this study have broader implications for sustainable agriculture, particularly in tropical and urban environments. The system's scalability and resource efficiency make it a viable option for expanding food production in areas where traditional farming

faces significant limitations. By reducing reliance on soil, optimizing water and nutrient use, and offering precise environmental control, automated hydroponic systems like this one represent a promising solution for addressing global food security challenges.

Future research could build upon this foundation by exploring the system's adaptability to other crops, refining sensor technologies to reduce drift, and conducting long-term studies on scalability and economic viability. Additionally, integrating renewable energy sources, such as solar panels, could further enhance the system's sustainability. As hydroponic farming continues to evolve, systems like this one offer a glimpse into the future of efficient, resilient, and environmentally friendly agriculture.

Acknowledgements

This work was supported by the Sistema Nacional de Investigaciones (SNI) of Panama of the Secretaría Nacional de Ciencia, Tecnología e Innovación de Panamá (SENACYT) (SNI-2R2024-020). The authors would like to thank the Universidad Tecnológica de Panamá, for their administrative support on the advancement of this project. And we would like to extend our thanks to the students in the applied programming course 2024.

Funding

The authors received no specific funding for this work.

Conflict of interest

The authors declare that they have no conflict of interest to disclose.

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