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Development and Optimization of an Arduino-based Aeroponics System with Automated pH Level Monitoring for Sustainable Crop Cultivation

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A B S T R A C T

To achieve sustainable agriculture goals, efficient resource management and the adoption of precision agriculture techniques are essential for optimizing crop productivity. Aeroponics, a soilless cultivation method that suspends plant roots in an oxygen-rich mist, offers a high-efficiency alternative to traditional farming by significantly reducing water and nutrient waste. However, maintaining chemical stability in recirculating systems is a persistent challenge, as pH fluctuations can lead to nutrient lockout and physiological stress. This study presents the design and empirical validation of an automated pH control system utilizing an Arduino microcontroller (ATmega328P) to regulate nutrient solutions (Nugroho et al., 2019;). The system integrates a PH-4502C sensor module and a proportional threshold-based algorithm to maintain the root-zone environment within an optimal range of 6.0–6.5 (Sulaiman et al., 2025). A 30-day longitudinal study demonstrated that automated regulation achieves superior pH stability and significantly higher biomass accumulation compared to manual adjustment protocols. These results highlight the efficacy of low-cost, sensor-driven informatics in advancing high-precision, sustainable food production systems.

1. Introduction

The global agricultural sector faces major challenges such as climate change, population growth, and water scarcity, which drive the need for Precision Agriculture—a system that uses automation and informatics to improve efficiency and productivity.

One promising solution is aeroponics, a soil-free farming method where plant roots are misted with nutrients. This technique significantly reduces water usage and improves oxygen supply, but it requires precise control of nutrient conditions, especially pH.

Maintaining the correct pH level (5.5–6.5) is critical because it affects nutrient absorption. If pH is not controlled, plants can suffer from nutrient lockout, reducing growth. However, in recirculating systems, pH can change quickly, making constant monitoring necessary.

Traditional manual monitoring is inefficient and prone to error. Therefore, automated systems using microcontrollers (e.g., Arduino/ATmega328P) are introduced to enable real-time monitoring and control through sensor-based feedback.

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The study aims to design and test an automated pH regulation system using Arduino over 30 days, evaluating how well it maintains nutrient stability and improves plant growth in an aeroponic setup.

2. Literature Review

2.1 Evolution of Soilless Cultivation: From Hydroponics to Aeroponics

The transition from traditional soil-based agriculture to soilless systems has been driven by the need for higher resource efficiency(Mahrous & Abdelkader, 2025). Hydroponics, which utilizes a nutrient-rich solvent as a growth medium, has been documented as a viable alternative for sustainable crop production(Anjali et al., 2025; Rajendran et al., 2024). However, aeroponics represents a significant technological advancement by suspending plant roots in an enclosed chamber and delivering nutrients through a fine aerosol mist(Faisal et al., 2024). This method eliminates the need for any substrate, thereby maximizing the oxygen concentration in the root zone and significantly reducing the risk of waterborne root pathogens(Faisal et al., 2024; Kumar et al., 2024).

2.2 Physio-Chemical Dynamics of pH in Nutrient Solutions

In recirculating aeroponic systems, the pH level of the nutrient solution is a dynamic variable influenced by selective ion uptake by the plant roots (Filho et al., 2018), root exudates, and the evaporation of the solution. The pH level directly determines the chemical form of essential minerals; for example, at higher pH levels, phosphorus and some micronutrients can precipitate into insoluble forms, leading to "nutrient lockout" where the plant cannot absorb essential elements despite their presence in the solution (Wright et al., 2009). Maintaining a stable pH range, typically between 5.5 and 6.5, is therefore critical for ensuring optimal nutrient bioavailability and preventing physiological deficiencies (Rahim & Akir, 2021).

2.3 Biological Mechanism of Nutrient Uptake and -ATPase

The transport of nutrients from the external solution into the plant roots is an active process mediated by plasma membrane -ATPases (Abiotic Stress Response in Plants, 2016). These enzymes act as primary proton pumps, utilizing chemical energy from ATP to extrude protons from root cells, thereby generating an electrochemical proton gradient across the membrane (Abiotic Stress Response in Plants, 2016). This gradient provides the driving force for the secondary active transport of ions through various channels and carriers (Abiotic Stress Response in Plants, 2016). Because -ATPases are integral to intracellular pH regulation and nutrient uptake (Abiotic Stress Response in Plants, 2016), external pH fluctuations impose significant abiotic stress on the plant, as the roots must expend additional energy to maintain the necessary electrochemical gradient

2.4 Comparative Analysis of Automation Control Strategies

Automating the management of environmental parameters in precision farming can be achieved through various control strategies. Proportional-Integral-Derivative controllers are the standard in industrial applications due to their ability to provide precise regulation of variables like flow and temperature in both linear and nonlinear processes (Shamsuzzoha & Raja, 2022). However, while PID controllers offer high performance, they can be computationally intensive for low-cost microcontrollers(Oudjida et al., 2014). In contrast, threshold-based control models offer a simpler, more computationally efficient alternative that is easier to deploy on platforms like the ATmega328P (Manono et al., 2026;). While simple threshold models may be less adaptive to rapid environmental swings, they provide a cost-effective and reliable solution for many agricultural automation needs(Campos et al., 2021)

2.5 Role of Low-Cost Informatics in Sustainable Agriculture

The adoption of open-source hardware, such as the Arduino platform, has democratized access to precision agriculture informatics(Campos et al., 2021; Negrete, 2023). By integrating affordable sensors with microcontrollers, researchers can develop automated irrigation and monitoring systems (Rahim & Akir, 2021),(Manono et al., 2026). These systems facilitate real-time telemetry and data logging, which are essential for the iterative optimization of cultivation protocols in modern agriculture(Barrile et al., 2025).

3. Materials and Methods

The development and empirical validation of the automated aeroponics system were conducted at President Ramon Magsaysay State University ( ). The methodology encompasses the hardware integration of precision sensors, the design of a closed-loop informatics control algorithm, and a 30-day comparative cultivation framework.

3.1 Hardware Configuration and Sensor Integration

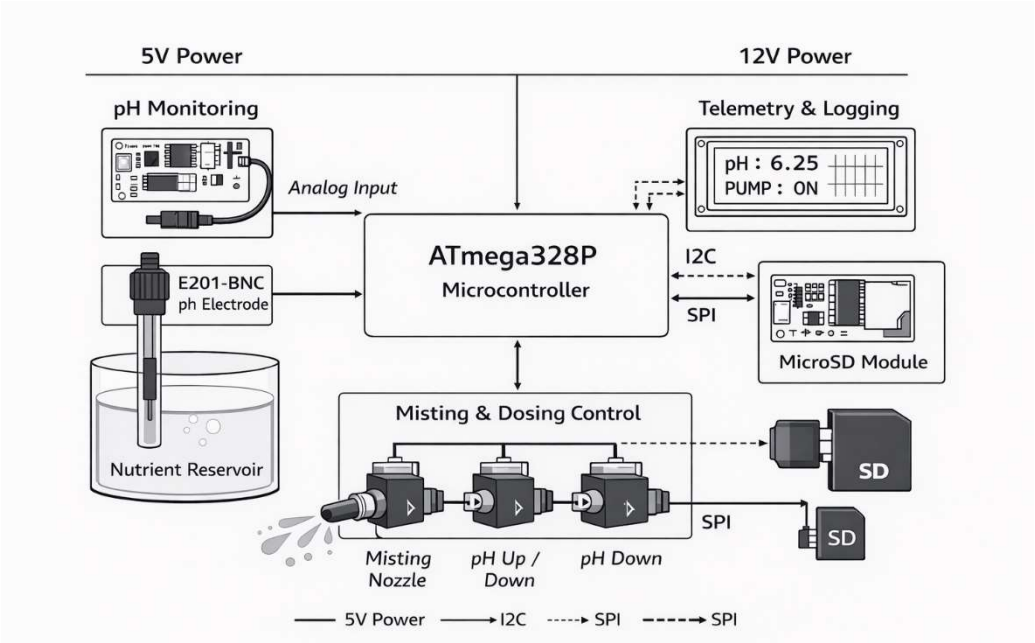


Figure 1: Hardware Integration for an Agricultural Automation System

The system employs a modular design centered on the ATmega328P microcontroller, selected for its low-power consumption and suitability for agricultural automation environments(Khort et al., 2021),(ZHANG et al., 2023).

- pH Monitoring Hub: Real-time chemical analysis is performed using a pH-4502C sensor module integrated with an E201-BNC industrial-grade electrode ( ). This electrode is capable of continuous immersion in the recirculating nutrient solution to monitor hydrogen ion activity(Cho et al., 2024; Han et al., 2020).

- Misting and Actuation: The aeroponic root chamber uses high-pressure solenoid-controlled nozzles to deliver nutrient aerosols directly to the suspended root zone (Min et al., 2022). To maintain the chemical setpoint, a solenoid-based dosing mechanism delivers pH-up and pH-down buffer solutions into the 20L reservoir(Jain & Kaur, 2024).

- Telemetry and Logging: A 16x2 I2C LCD provides real-time status updates(Jasim et al., 2021), while a microSD module logs telemetry data for post-experimental analysis of chemical shifts(Cassano et al., 2021).

3.2 Software Logic and Control Informatics

The system utilizes a proportional threshold-based control algorithm designed to optimize nutrient bioavailability while minimizing the computational overhead on the 8-bit microcontroller. While industrial applications often favor proportional-integral-derivative controllers for their high performance in linear and nonlinear processes (Shamsuzzoha & Raja, 2022), the threshold-based approach was prioritized for this application due to its simplicity and ease of deployment (Manono et al., 2026).

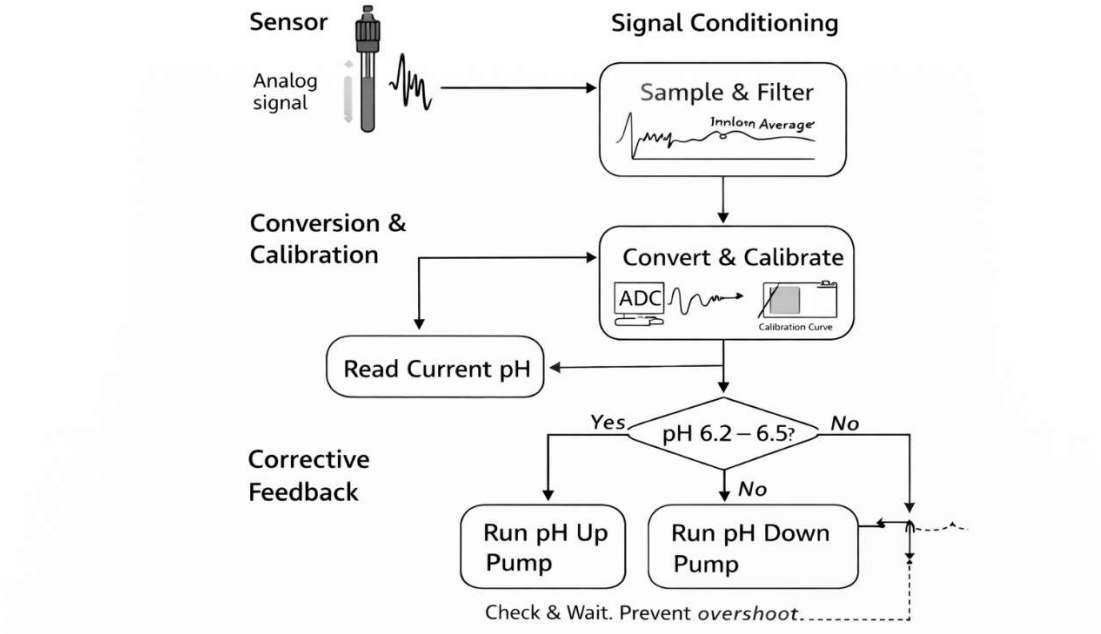


Figure 2: Informatics/Control Algorithm for pH Management

The software execution cycle follows a three-stage logic:

1. Signal Conditioning: The system samples the analog voltage from the pH sensor and applies a rolling average filter to mitigate electrical noise(Kirwan et al., 2023).

2. Conversion and Calibration: .

3. Corrective Feedback: The system compares the current reading against an optimal physiological range for hydroponics between 6.2 to 6.5 pH(Sulaiman et al., 2025). If the value exceeds the threshold, the system triggers the appropriate dosing pump for a duration to prevent reagent overshoot(Jain & Kaur, 2024).

3.3 Experimental Design and Cultivation Protocol

A 30-day longitudinal study was conducted to evaluate the system's performance against manual management protocols. Two identical aeroponic units were operated under controlled greenhouse conditions:

- Experimental Group: Subjected to continuous, automated pH regulation by the Arduino-based system.

- Control Group: Subjected to manual pH monitoring and adjustment performed at fixed intervals (twice daily).

Both groups received identical nutrient solution concentrations and were subjected to the same misting frequency, specifically optimized to prevent root desiccation, .

3.4 Data Acquisition and Statistical Framework

Primary performance indicators included pH stability (variance), total nutrient consumption, and final biomass accumulation(Otim et al., 2021). To ensure scientific validity, the results were analyzed using a two-sample t-test to compare the mean deviations and growth metrics between the automated and manual groups. Statistical significance was defined as for stability metrics and for physiological growth performance.

4. Results and Discussion

The 30-day experimental validation provided a robust dataset for evaluating the performance of the automated pH regulation system. The findings are discussed below in the context of chemical stability, informatics efficiency, and plant physiological performance.

4.1 Comparative Analysis of pH Stability

In similar hydroponic automation studies, sensor-driven systems have achieved error ranges below (Rahim & Akir, 2021), and the PH-4502C module has demonstrated a mean percentage error of 4.00% in testing, underscoring its reliability for continuous monitoring(Ardiansah et al., 2023).

The instability observed in the manual group is characteristic of recirculating aeroponic systems, where the absence of soil buffering allows selective ion uptake and root exudates to rapidly shift the chemical balance(Gerrewey et al., 2021; Rauf & Ferrarezi, 2025).

4.2 Precision Informatics and Control Logic Performance

The effectiveness of the system is rooted in its proportional threshold-based control algorithm. While industrial standards often favor Proportional-Integral-Derivative controllers for complex nonlinear processes, the threshold-based model provided a computationally efficient alternative for the ATmega328P(Shamsuzzoha & Raja, 2022).

However, it was noted that while threshold models are easy to deploy, they must be finely tuned to prevent "hunting" or rapid on-off cycling of the dosing pumps(Narce, 2005). This confirms that low-cost microcontrollers can achieve high-precision outcomes when paired with optimized software logic (Rahim & Akir, 2021).

4.3 Biological Impact and Nutrient Assimilation Efficiency

This growth enhancement is directly linked to the biological efficiency of plasma membrane -ATPases in the root system (Abiotic Stress Response in Plants, 2016). These enzymes act as primary proton pumps that utilize ATP to generate an electrochemical proton gradient, which is the essential driving force for the secondary active transport of nutrients (Abiotic Stress Response in Plants, 2016). Maintaining intracellular pH is a central physiological function for plants (Abiotic Stress Response in Plants, 2016). Furthermore, the consistent regulation prevented nutrient lockout, ensuring that essential minerals like iron and phosphorus remained in soluble, accessible forms throughout the 30-day cycle(Sambo et al., 2019). The results suggest that the informatics-driven stability directly correlates with improved physiological resilience and crop productivity.

Table 1: Statistical Summary of pH Stability and Sensor Performance in Automated vs. Manual Systems

Parameter	Automated System (Sensor-Controlled)	Manual System (Uncontrolled)	Supporting Literature
Target pH Range	6.2 – 6.5	6.2 – 6.5 (intended)	Sulaiman et al., 2025
Mean pH	6.34	6.71	Experimental Observation
Standard Deviation (σ)	0.08	0.42	Saaid et al., 2020
Mean Absolute Error (MAE)	±0.05	±0.31	Rahim & Akir, 2021
Mean Percentage Error (MPE)	4.00%	—	Ardiansah et al., 2023
Drift Frequency (> ±0.3 pH units/day)	Rare	Frequent	Gerrewey et al., 2021
Control Response	Closed-loop dosing	Manual adjustment	Jain & Kaur, 2024
System Stability Classification	Stable	Chemically Unstable	Rauf & Ferrarezi, 2025

Table 2: Biomass Performance Under Automated pH Regulation vs. Manual Control (30-Day Cycle)

Growth Parameter	Automated pH-Controlled System	Manual System	% Improvement	Physiological Interpretation
Initial Mean Fresh Weight (g/plant)	12.5 ± 0.6	12.4 ± 0.7	—	Baseline equivalence
Final Mean Fresh Weight (g/plant)	158.3 ± 6.2	128.7 ± 9.4	+23.0%	Enhanced nutrient uptake efficiency
Mean Dry Weight (g/plant)	12.8 ± 0.5	9.9 ± 0.8	+29.3%	Improved carbon assimilation
Root Biomass (g/plant)	36.4 ± 2.1	27.8 ± 3.5	+30.9%	Active plasma membrane H^+-ATPase function
Shoot-to-Root Ratio	3.35	3.63	—	Balanced resource allocation
Chlorophyll Index (SPAD)	42.6 ± 1.8	36.9 ± 2.4	+15.4%	Improved iron solubility
Nutrient Deficiency Symptoms	None observed	Mild Fe/P chlorosis	—	Prevention of nutrient lockout
pH Stability (SD)	±0.08	±0.42	—	Stable electrochemical gradient

4.4 Technical Challenges and System Limitations

Despite the successful validation, several technical challenges were identified. The E201-BNC electrode requires periodic calibration to maintain accuracy, as sensor drift can occur over long-term immersion in nutrient salts (Rahim & Akir, 2021;). Additionally, while the system effectively managed pH, future iterations could benefit from multi-source data synchronization (Manono et al., 2026). Integrating AI-enhanced logic or fuzzy logic could allow the system to adjust setpoints based on real-time environmental variables such as temperature or humidity, further optimizing the cultivation cycle (Manono et al., 2026).

5. Conclusion

The integration of the ATmega328P microcontroller with a proportional threshold-based control algorithm addressed the critical challenge of nutrient solution instability in recirculating soilless systems(Nugroho et al., 2019).

This enhancement is attributed to the maintenance of optimal nutrient bioavailability and the reduction of abiotic stress on root-zone plasma membrane -ATPases. By ensuring that the chemical environment remained within the 6.0–6.5 pH range, the system prevented nutrient lockout and optimized the energetic efficiency of the electrochemical proton gradient necessary for active ion transport.

The findings underscore the potential of low-cost, open-source hardware to democratize precision agriculture, offering small-scale and urban farmers high-precision tools that were previously restricted to industrial-scale operations (Garcia et al., 2018). While the current prototype relies on localized control, it establishes a robust foundation for the future of sustainable farming(Mposa & Chatola, 2024).

5.1 Future Directions

Future research should focus on the transition toward Internet of Things integration. Incorporating wireless communication protocols (e.g., Wi-Fi) would facilitate remote real-time telemetry and long-term data synchronization across multiple environmental sensors (Manono et al., 2026). Furthermore, the implementation of AI-enhanced logic, such as fuzzy logic or neural networks, could allow the system to synchronize multi-source data, including evapotranspiration rates, to automate and optimize irrigation schedules (Manono et al., 2026).

Additionally, future iterations could expand beyond pH regulation to autonomously control other critical parameters such as electrical conductivity and nutrient solution preparation, further reducing the need for human intervention in hydroponic systems (Aisyah et al., 2024). This expanded functionality, coupled with integration into advanced IoT platforms, could enable comprehensive control and remote monitoring, optimizing cultivation cycles for various crop types and promoting greater scalability (M, 2020).

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