



**(SPECIAL ISSUE OF NATIONAL CONFERENCE ON INTEGRATING
INFORMATION TECHNOLOGY FOR SUSTAINABLE AND INNOVATIVE
FINANCIAL MANAGEMENT [NC-ITSIFM-2026], JULY 04, 2026, ACADEMIA
INTERNATIONAL COLLEGE, LALITPUR, NEPAL)**

Automated Nutrient Dosing and Monitoring System for Hydroponic Crop Production

**Aradhya Dhungel^{1*}, Dikshya Khatri², Nischal Dangol³, Pankaj Kumar Mehta⁴,
Anup Shrestha⁵**

¹Dept. of Electronics and Computer Engineering, Thapathali Campus, Nepal

Email: aradyadhungelr@gmail.com

²Dept. of Electronics and Computer Engineering, Thapathali Campus, Nepal

Email: dikshyakhatri333@gmail.com

³Dept. of Electronics and Computer Engineering, Thapathali Campus, Nepal

Email: nischaldangol007@gmail.com

⁴Dept. of Electronics and Computer Engineering, Thapathali Campus, Nepal

Email: 123pankajmehta@gmail.com

⁵Asst. Professor, Dept. of Electronics and Computer Engineering, Thapathali Campus, Nepal

Email: anup@tcioe.edu.np

Original Article

Correspondence Author*

Received: Jul 07, 2026

Revised: Jul 12, 2026

Accepted: Jul 18, 2026

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ABSTRACT

This research demonstrates the design and implementation of an automated hydroponic system allowing soil-less growth of crops for efficient resource consumption and improved yield and productivity as compared to conventional farming. Hydroponics refers to the water-based



cultivation method in which plants are grown in a solution with calculated nutrient quantities for individual crops. With the increasing global demand for food security as well as the decline in arable land, hydroponic systems offer a better alternative to meet agricultural needs in both urban and rural settings. The designed system consists of sensors such as pH sensor and EC sensor, an ESP32-WROOM32 microcontroller-based control unit, and automated actuators to continuously monitor and regulate key parameters. Automation of the nutrient solution is done through a closed-loop control of pH and EC of the solution where the sensors provide real-time feedback to the controller, which compares measured values with predefined crop-specific standard EC and pH ranges. On the basis of these parameters, dosing pumps are used to add required quantities of acid, base, or concentrated nutrient solutions to compensate for deviations in the nutrient rich solution. Calibration routines are set at periodic time intervals to ensure that the sensor accuracy and prolonged system reliability is attained. By minimizing the amount of water used and optimized nutrient delivery, the proposed system presents a scalable and sustainable solution for modern agriculture.

Keywords: closed loop algorithms, dosing, ESP32, EC, hydroponic, pH

1. INTRODUCTION

Hydroponics requires constant monitoring and utmost precision, which is difficult to achieve through manual labour, but is generally done manually. Parameters such as pH, EC, and humidity differ from plant to plant, which must be provided with a minimum tolerance. Even small deviations, if unnoticed for a longer time, which is very likely with manual models, can cause nutrient deficiencies, root stress, and ultimately crop loss. Also, in a manual system, logs and feedback in real-time are unavailable. All the mentioned cases affect the overall efficiency of crop production. Although automation in hydroponics has been around for some time, the existing systems lack stability aware dosing methods and threshold-based control strategies which is also suitable for low cost embedded systems.

Designed specifically for lettuce to ensure precise control during experimentation, this hydroponic automation system utilizes a closed-loop pH and EC control mechanism to guarantee accurate nutrient distribution. By integrating automated pumps and sensors, it significantly minimizes human interaction, thereby reducing the potential for manual errors. This robust system is highly applicable in regions facing land or water scarcity, while its affordability and scalability make it an ideal solution for small farms, home systems, and educational institutions alike. Ultimately, the system promotes sustainable farming practices through the highly effective utilization of water and nutrients.

2. LITERATURE REVIEW

Gericke's 1937 study [1] demonstrated that plants could grow and complete their life cycle with roots submerged in a nutrient-rich solution, supporting the commercial feasibility of



soilless farming. This study established the foundation for the field of hydroponics and laid the foundation for modern Controlled Environment Agriculture (CEA). Through this foundation, Savvas and Gruda [2] highlighted that soilless cultivation technologies delivered higher crop production, uniform plant growth, and significantly reduced soil quality dependency. Barbosa et al. [3] then conducted a comparative analysis of lettuce production, strengthening the case for hydroponics. The comparison between hydroponic and conventional farming methods showed that hydroponics can reduce water consumption by 70-90% through the recirculation of nutrient solutions, minimizing losses from evaporation and percolation. Trejo-Téllez and Gómez-Merino [4] further elaborated on the principles of direct ionic nutrient delivery to the roots and the formulation of nutrient solution, emphasizing the importance of maintaining the pH of the solution within a slightly acidic range of 5.5 to 6.5 for most crops to achieve optimal nutrient availability and overall plant performance.

Hansen [5] further investigated the operational complexity of hydroponic systems, analyzing the interdependence between pH and Electrical Conductivity (EC), and warned that imbalances in either parameter can result in osmotic stress, nutrient lockout, deficiencies, or toxicities that directly affect yield and crop quality. Expanding the scope of comparison, Nam et al. [6] investigated the effects of nutrient solution cooling on leaf lettuce in hydroponic systems. This established the importance of precise environmental and solution parameter management to maintain consistent root-zone conditions and healthy crop development. Finally, Kumar et al. [7] provided a comprehensive review of IoT as a transformative technology, concluding that IoT-based frameworks substantially enhance system traceability, offer robust decision-support capabilities, enable continuous remote monitoring without physical presence, and open pathways for integrating advanced predictive control techniques including machine learning models for data-driven optimization in modern hydroponic applications.

3. METHODOLOGY

A. System Overview

The automated hydroponic system is designed to maintain nutrient level and environmental conditions through continuous monitoring and closed loop control. It consists of three sensors which are pH, TDS, and temperature and humidity sensors, an ESP32 based control unit, and cloud-based monitoring to regulate pH, EC, and humidity for hydroponic crop cultivation. The entire system is powered by an AC power supply.

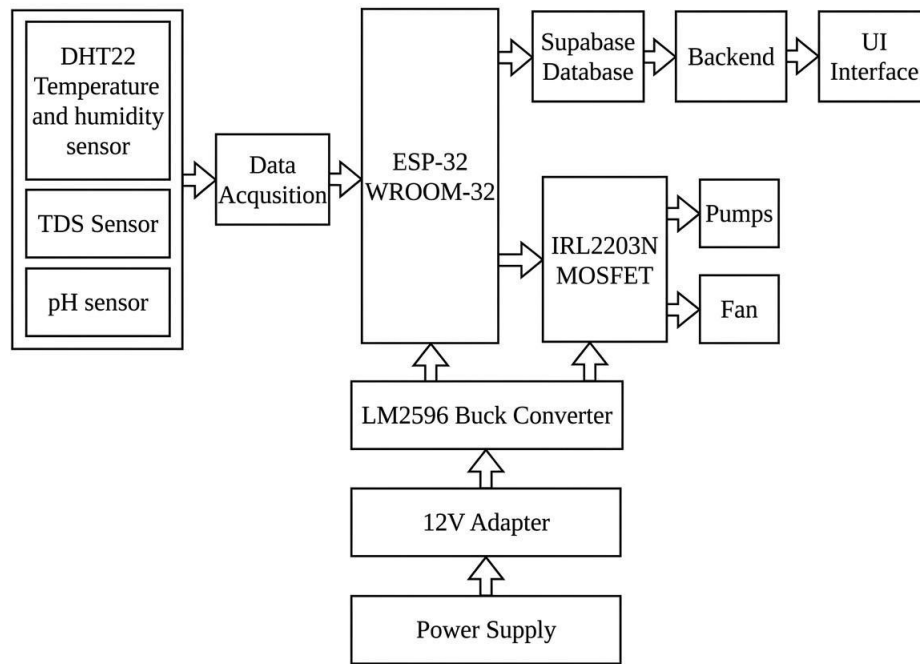
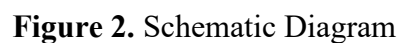


Figure 1. Block Diagram

B. Working Principle

The experimental procedure of the proposed design is performed using an automated setup that operates in crop growth cycles of lettuce (*Lactuca sativa*). Lettuce is a suitable crop for hydroponic cultivation as it has a short growth cycle, a comparatively low demand for nutrients, and is resistant to significant parameter variations in nutrient solutions such as pH and EC. This design consists of a closed-loop automated control of pH and EC based on the predefined setpoints provided for the crop. Saplings are first transplanted into the hydroponic system. During the experimental period, the system monitors the parameters of the nutrient solution in intervals of 10 minutes and reacts autonomously through corrective dosing according to the deviation from the specified range of pH and EC. Furthermore, stabilization delays are applied after each dosing process to allow the nutrients to mix uniformly before measurements are taken. During each dosing event, the system introduces a priority-based control sequence in which EC is balanced before adjusting pH. This is because the concentration of nutrients in the solution influences the acidity of the solution. Conventional IoT based hydroponic systems generally enforce immediate threshold triggered nutrient dosing, where corrective dosing is applied as soon as parameter deviations are detected. In such cases, the delay in mixing is overlooked, leading to nutrient overshoot. To solve this problem, a stabilization delay and threshold based control is implemented in the system.

C. Hardware Schematic Design



A PCB (Printed Circuit Board) was fabricated based on the above schematic, bringing all electronic hardware components together for ease of debugging, and fast repair or replacement if needed.

pH Monitoring and Calibration

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corresponding pH:

$$pH = 7 - \frac{MID_PH_v - pH_raw_v}{CALIBRATION_FACTOR}$$

where,

pH = calculated acidity or alkalinity of the solution,

MID_PH_v = reference midpoint value in volts at pH 7,

pH_raw_v = raw sensor reading in volts,

$CALIBRATION_FACTOR$ = constant used for calibration.

The optimal pH range for lettuce was 5.5-6.5 pH but was kept at 6.0-6.5 pH to avoid overdosing. A pen-type pH meter was used to measure the pH of the solution at any given time. When the pH reading exceeded the threshold of 6.5, a certain amount of acid was automatically dosed into the 15-liter reservoir that held the solution. The acid used to lower the pH was Phosphoric acid solution with a pH of 1.4. The volume of acid to be dosed was calculated to be 0.15 ml through the dosing pump runtime, the pH of the Phosphoric acid, and the volume of the solution which were 250ms, 1.4, and 15 liters respectively.

TDS Monitoring

For TDS monitoring, a conductivity probe was connected to the TDS module, which outputted an analog signal. The TDS sensor measured Total Dissolved Solids concentration by converting the electrical conductivity measurement into TDS. The conversion of electrical conductivity into TDS is done by:

$$TDS = EC * k \quad (2)$$

Where, k = conversion factor ranging 0.4 to 0.7

The optimal TDS range for lettuce was 560-840 ppm but it was kept at 630-690 ppm to avoid overdosing as well as constant dilution. When the TDS of the solution was lower than the threshold of 630 ppm, dosing pumps were activated automatically. The nutrient solution dosed to increase TDS was prepared from NPK 19-19-19, Calcium Nitrate, Epsom Salt and distilled water. Two solutions A and B were prepared and stored in wash bottles.

A priority-based control strategy was implemented in which TDS correction was always performed prior to pH adjustment. In this way, the interaction between changes in the concentration of nutrients and the acidity of the solution is isolated, improving the stability of the overall system and reducing the possibility of repeated corrective actions.

IoT Communication and Data Logging

To provide monitoring as well as analysis, an Internet of Things (IoT) communication framework was integrated. The Wi-Fi module of the ESP32 microcontroller was used to establish communication with a cloud-hosted backend. Sensor readings were transmitted in the periodic



interval of 10 minutes using HTTP requests and stored using a cloud database. The record consists of parameter values such as pH and TDS as well as timestamps, which helps to provide information for the analysis of the system performance. Data collection also provides helpful information for understanding nutrient consumption patterns and dosing activity during the entire crop cycle.

A web-based dashboard acts as the user interface for monitoring the current parameters and provides a control panel for the hydroponic system. It provides real-time sensor readings in the form of cards and graphs as well as past readings to a certain extent. It also allows configuration of the thresholds of control parameters and dosing pump duration.

4. RESULTS

The pH fluctuation graph recorded over 1 week (168-hour period) demonstrates that the closed-loop control system works consistently within the optimal range of 6.0 to 6.5 for lettuce cultivation. A recurring sawtooth pattern is observed, which is characteristic of threshold-based control. In each cycle, the pH increases gradually due to the absorption of anions such as nitrate and phosphate by the lettuce roots as a result of the nutrient dosing, which progressively alkalizes the solution. When the pH reaches the set limit of 6.47, the acid dosing pump is activated, which delivers a measured quantity of pH-down solution that brings the value down to approximately

6.1 to 6.2 (dashed red line on the graph), then after some time the natural gradual upward drift can be seen again after the observed sharp drop occurred due to adding acidic pH solution.

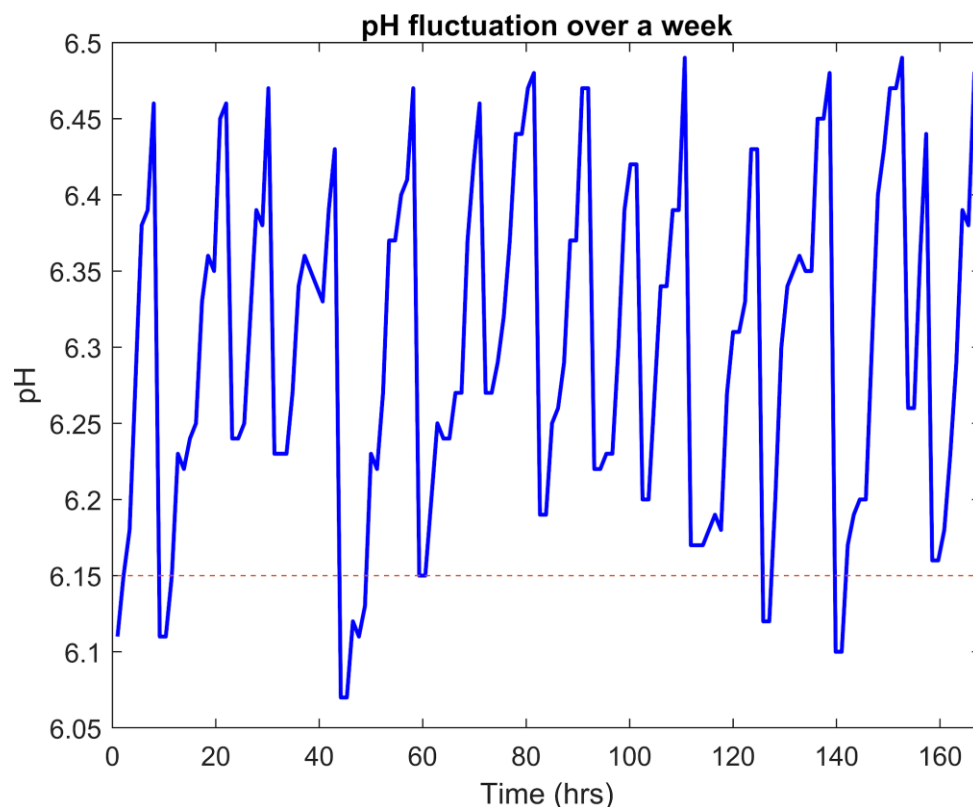




Figure 3. pH Fluctuation Graph over a week

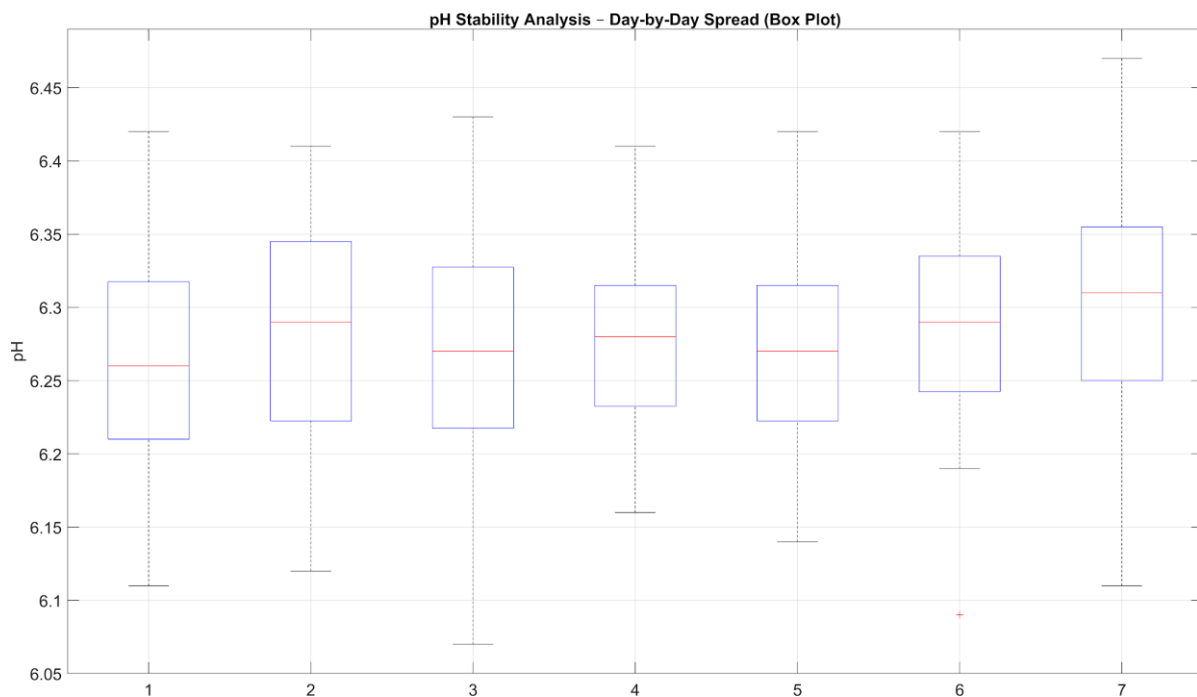


Figure 4. pH stability daily box plot distribution over a week

The following figure represents the interpolated line of best fit for pH estimation obtained by



measurement of electrode voltages in 3 respective buffer solutions with values:

$$pH_{4.00} \approx 1.3353V, \quad pH_{6.86} \approx 1.1871V, \quad pH_{9.18} \approx 1.0666V$$

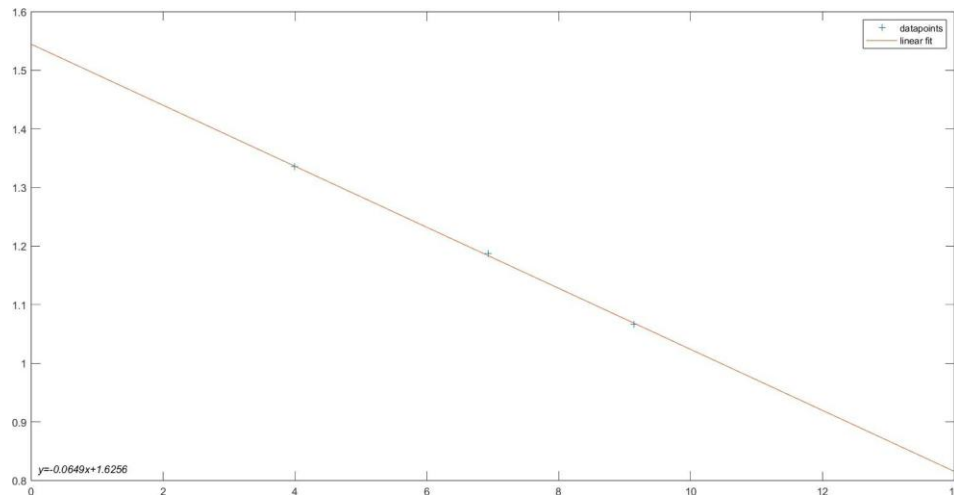


Figure 5. Electrode voltage vs pH interpolation

By interpolation we obtained MID $P_{H_v} \approx 2.08V$ which was later used to map voltage values to pH using equation (1).

TDS deviation over a 1 week time period was studied. During the first 40 hours, a steep continuous decline was observed from ~ 780 units to ~ 640 units i.e. a drop of ~ 140 units before the first dosing correction event occurs. The decline is slightly steeper than the expected

~ 65 units drop per day for mature stages of lettuce, and is attributed to the initial TDS value being in the upper quarter of the threshold range. From 40 hours onward, a sawtooth oscillation is observed between the ranges of approximately 630 to 690 units, demonstrating activation of the nutrient dosing pump at 640 units (dashed red line) to compensate for the decline caused by plant uptake and evaporation. When a dosing event occurs, it produces a sharp upward correction of 30 to 60 units. After some time, a gradual decline can be observed as nutrients are consumed by the plants.

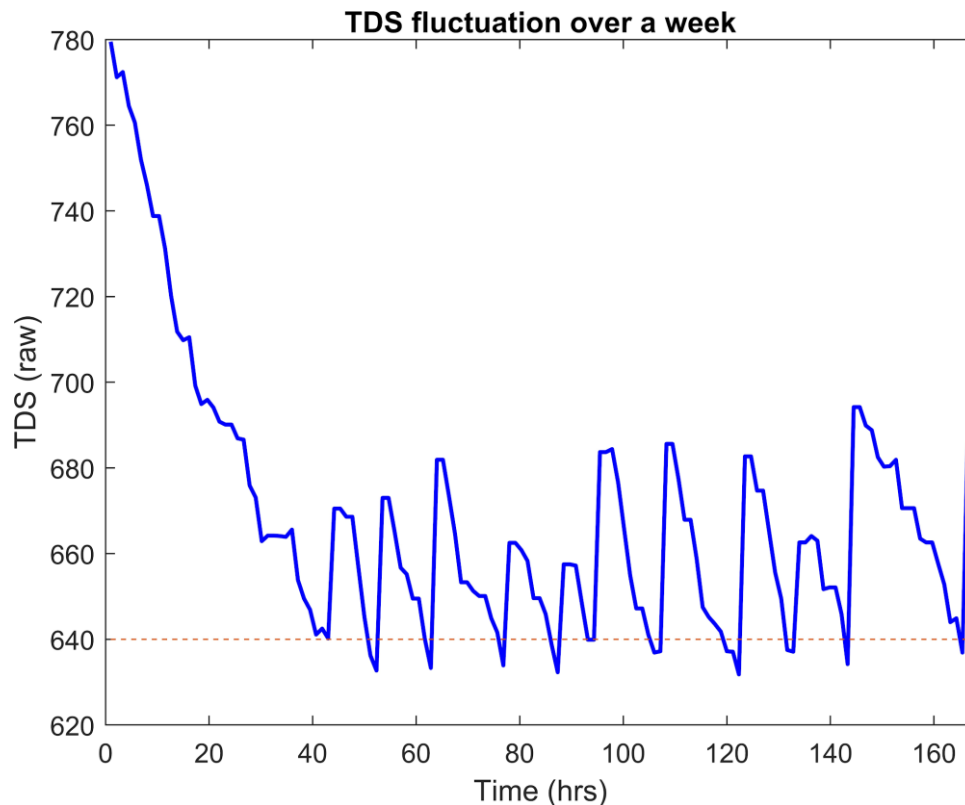


Figure 6. TDS Fluctuation Graph over a week

The bar graph below shows the comparison between the performance of the hydroponics system before and after automation. The comparison is done across four selected performance indicators; pH deviation, EC deviation, monitoring frequency, and frequency of manual intervention.

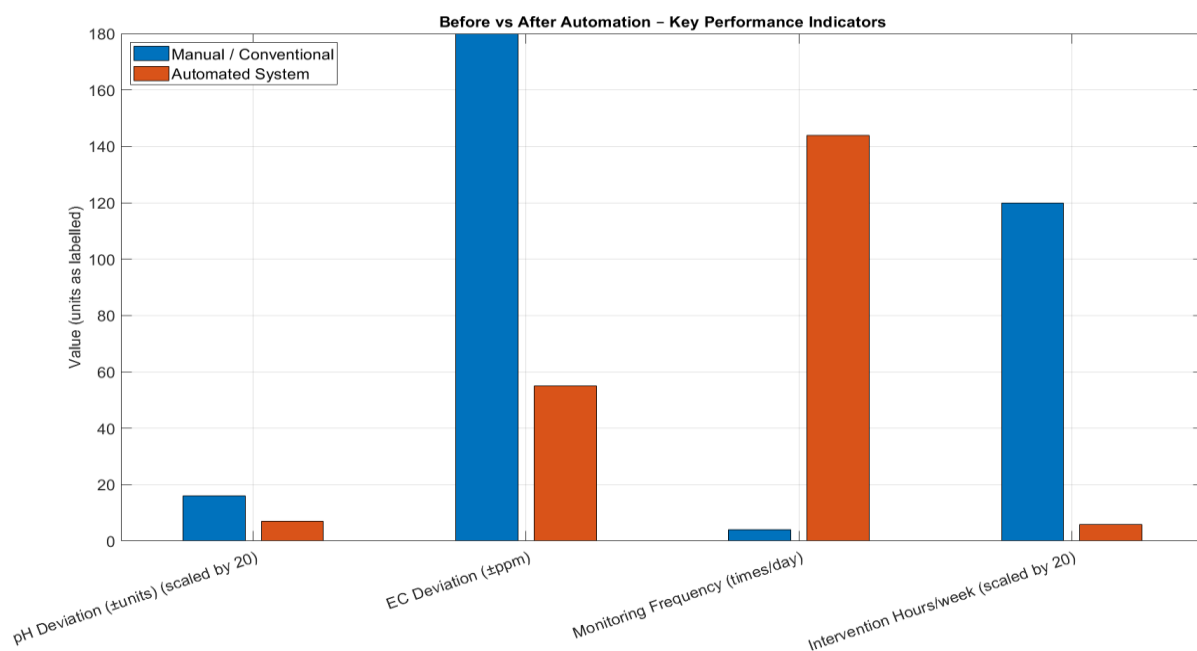


Figure 7. Before vs After Automation - Performance Comparison



The table below summarizes all obtained improvements of the designed system.

Table 1. System performance vs benchmark targets

S.N.	Performance Metric	Manual System (Reference)	Designed System
1	pH deviation ($\pm$ units)	0.6 - 1.2	0.30 - 0.38
2	EC deviation ($\pm$ ppm)	150 - 300	30 - 60
3	Monitoring frequency	2 - 4 $\times$ /day	144 $\times$ /day
4	pH correction time (min)	30 - 120	5 - 10
5	EC correction time (min)	30 - 120	5 - 10
6	Human labour (h/week)	4 - 8	$\sim$ 0.3
7	Sensor accuracy - pH ($\pm$)	$\pm$ 0.2 typical	$\pm$ 0.1
8	Sensor accuracy - TDS (%)	$\pm$ 5% typical	$\pm$ 2.5%

5. FUTURE WORK

Future work will focus on upgrading the system by multiple crop support as well as adaptive setpoints based on crop growth stages, which increases the applicability. Machine learning-based predictive control can be added to predict nutrient consumption, optimize dosing schedules, and detect sensor anomalies such as calibration drift before they affect the performance. Additionally, integrating automatic calibration and using industrial-grade sensors will improve measurement accuracy and reliability. Also, the development of a dedicated mobile application with real-time monitoring, alerts, and remote control capabilities will further enhance system usability and provide availability of scalable and practical hydroponic applications.

6. CONCLUSION

The designed system for hydroponic crop production demonstrated the integration of embedded systems, sensing technologies, and IoT based data management to mitigate the drawbacks of traditional hydroponic systems. The developed system has managed to achieve closed loop control to control key nutrient parameters, namely pH and electrical conductivity (EC) with significantly reduced human interaction.

An important advancement made by this system is the implementation of a threshold-based



closed loop control strategy with stabilization delay, which is most appropriate to use in the hydroponic systems with a slow response. Compared to traditional PID-based techniques, the offered method is simpler to compute and avoids issues such as overshoot and oscillations, making it highly suitable for low cost microcontroller platforms.

Over a 1 week(168 hour) validation period of 1 week, the system maintained pH within a deviation of ± 0.38 units and EC within ± 60 units of their respective setpoints compared to ± 0.8 pH units and ± 180 EC units for manual systems, satisfying the defined requirements of ± 1.0 pH units and ± 200 EC units respectively. The correction response is applied correctly across the week without any of the values crossing the defined boundaries for a prolonged duration. Monitoring frequency increased from ≥ 4 manual checks per day to 144 automated readings per day, while operator intervention was reduced from an estimated 4 - 8 hours per week to 0.3 hours per week. Corrective response for both pH and EC deviations was consistently achieved within 5 - 10 minutes of threshold breach.

Some hardware limitations like the instability of ADC pins and sensor drift during testing were identified. The most significant of these was the progressive drift of the commercial pen-type pH electrode under continuous immersion, which necessitated manual recalibration every four days and poses the primary reliability risk for long term unattended operation of this whole system.

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