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SMAC: System for monitoring and automatic control of water, nutrients, and pH in hydroponic nutrient film technique

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ABSTRACT

Manual regulation of nutrient solution parameters in hydroponic systems often causes instability and delayed corrective actions. This study presents an Internet of Things (IoT) based system monitoring and automatic control (SMAC) for a nutrient film technique (NFT) hydroponic system to automatically regulate pH, total dissolved solids (TDS), and temperature. The proposed system integrates real-time sensors, automatic actuators, and dual-microcontroller architecture, in which an Arduino Uno performs local control while an ESP32 enables wireless IoT monitoring. An experimental systems engineering approach was applied for system design and performance evaluation. Automatic temperature compensation (ATC) was incorporated into pH and TDS measurements to improve reliability under varying thermal conditions. Experimental results indicate that the temperature sensor achieved an average error of 0.13 °C. The control algorithm corrected pH deviations gradually by approximately ±0.31 pH units (pH Up) and ±0.38 pH units (pH Down) per cycle without overshoot. Nutrient concentration control increased TDS by about 75 ppm per cycle under low-TDS conditions. Stability testing confirmed that pH and TDS remained within optimal ranges after disturbances, while safety mechanisms operated reliably under abnormal temperatures. The results demonstrate that the proposed SMAC system provides accurate, stable, and adaptive control suitable for precision and sustainable hydroponic applications.

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1. INTRODUCTION

In the context of modern agriculture, hydroponic systems have emerged as one of the most innovative approaches to improving crop production efficiency, particularly in regions with limited agricultural land. Rapid population growth and the expansion of urban areas have led to a significant reduction in productive land. These conditions necessitate the development of agricultural innovations that do not rely on conventional soil-based cultivation. Hydroponic systems offer a viable solution through soilless cultivation methods that utilize alternative media such as gravel, peat, or vermiculite enriched with nutrient solutions. This approach enables more precise control of the growing environment, including nutrient delivery, pest management, and disease control, thereby allowing plants to grow more optimally and achieve higher quality yields.

Nevertheless, the implementation of hydroponic systems in various regions, including Indonesia, still faces limitations in terms of monitoring and management of plant growth parameters [1]. Most existing hydroponic systems continue to rely on manual measurements of nutrient concentration and pH levels using conventional instruments such as total dissolved solids (TDS) meters and pH meters [2], [3]. This process is repetitive, time-consuming, labor-intensive, and prone to human error in data collection. Inaccurate regulation of nutrient concentration and pH can result in physiological stress in plants, reduced productivity, and even crop failure [4]. These challenges highlight an urgent need for automated control systems capable of operating in real time to maintain stable growing conditions [5]–[7].

Although several hydroponic monitoring systems have incorporated Internet of Things (IoT) based data acquisition, most existing solutions still function primarily as monitoring platforms and offer limited capability for adaptive, real-time control. Current systems rarely integrate automated nutrient dosing, pH regulation, or temperature-aware compensation, resulting in unstable growing conditions when environmental parameters fluctuate. This limitation indicates a clear research gap in developing an IoT-enabled hydroponic system with fully integrated automation for nutrient and pH management, supported by recent studies that highlight similar shortcomings [8], [9]. The integration of these technologies has the potential to create intelligent hydroponic systems capable of adaptive and efficient monitoring and control of environmental variables [10]. Such systems are expected not only to enhance precision in plant maintenance but also to reduce dependence on manual intervention [11].

Based on this background, this study aims to develop system monitoring and automatic control (SMAC), an IoT-based automated system designed to monitor and regulate pH and TDS levels in a nutrient film technique (NFT) hydroponic system. The novelty of this research lies in the implementation of an automatic temperature compensation (ATC) mechanism integrated into a sensor-based adaptive control system, which enables real-time correction of pH and TDS measurements based on variations in nutrient solution temperature. By incorporating temperature-aware compensation, the system dynamically adjusts nutrient dosing and pH regulation according to actual plant requirements under fluctuating thermal conditions. This approach improves measurement accuracy, control stability, and nutrient-use efficiency, thereby contributing to the development of precision, intelligent, and sustainable hydroponic agriculture.

The main contributions of this study are as follows: Development of an IoT-based hydroponic control system using a dual-microcontroller architecture, enabling distributed sensing, actuation, and cloud integration. Integration of an ATC mechanism for pH and TDS measurements to enhance accuracy under fluctuating thermal conditions. Experimental validation of the system, demonstrating improved stability, measurement accuracy, and adaptive response in maintaining optimal hydroponic nutrient conditions.

2. METHOD AND PROPOSED DESIGN

This study uses an experimental, systems engineering approach to design, implement, and test an IoT-based automated hydroponic control system integrating pH, TDS, and temperature sensors. The system maintains optimal nutrient conditions in real time, improving maintenance efficiency and supporting healthier plant growth.

2.1. Hydroponic NFT method

Hydroponic systems consist of several types, including the wick system, drip system, ebb and flow system, deep water culture, NFT, and aeroponics [12], [13]. The NFT hydroponic method operates by flowing a thin layer of nutrient solution through channels positioned at a certain height [14], enabling plant roots to continuously receive nutrients and oxygen while simultaneously preventing root rot. The primary advantage of the NFT system lies in the stability of water and nutrient supply that is consistently available around the plant roots. This system is most suitable for plants with small root structures, such as strawberries, celery, and lettuce. The NFT method was selected for automated control: continuous flow enables rapid detection and response, shallow layers improve efficiency, and simple channels ease integration with sensors, actuators, and IoT monitoring.

The proposed system utilizes an NFT setup equipped with SMAC, a custom-developed platform designed to maintain nutrient concentration and pH levels automatically in real time. Unlike previous hydroponic systems, which primarily focus on monitoring without adaptive control capabilities [15], the SMAC system actively regulates nutrient addition and pH adjustment based on real-time sensor inputs. The control algorithm modulates the delivery of AB mix solution and pH-balancing agents to maintain conditions within recommended thresholds—560 to 840 ppm for nutrient concentration [16], [17] and 5.5 to 6.5 for pH levels [18], [19].

This approach not only enhances the efficiency of hydroponic system maintenance but also minimizes human intervention, reduces the risk of measurement errors, and enables remote monitoring and control through an IoT platform. Consequently, the proposed NFT-based SMAC hydroponic design provides a substantial improvement in system adaptive response, resource utilization efficiency, and stability of plant growth conditions compared to previously developed automated systems.

2.2. System architecture

The system integrates hardware and software for real-time monitoring and automated hydroponic control using dual-microcontroller architecture. The Arduino Uno handles precise sensor readings (pH, TDS, temperature) and actuator control, while the ESP32 manages Wi-Fi communication and data processing. Sensor data are transmitted via universal asynchronous receiver/transmitter (UART) to the ESP32, which publishes them to Blynk platform for remote monitoring [20]. This design enhances modularity, reduces processing load, and ensures reliable local control despite network instability. Figure 1 presents the complete system architecture, including the controllers, sensors, actuators, communication pathways, and IoT interface. Arduino Uno was chosen for its stable ADC and reliable control of pH, TDS, and temperature sensors. The ESP32 provides Wi-Fi and higher processing for IoT communication. Separating control (Arduino) and networking (ESP32) improves modularity, reduces interference, and ensures continuous operation under unstable connectivity. Both are cost-effective, widely supported, and suitable for scalable hydroponic automation.

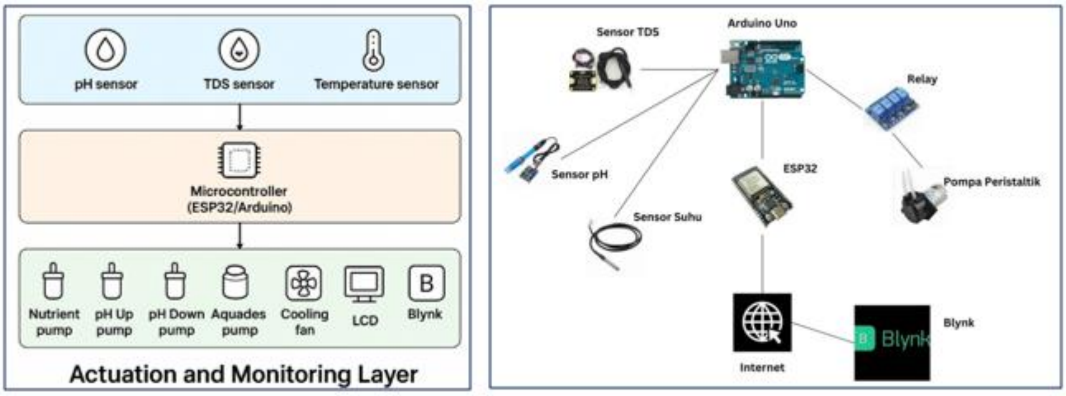

Figure 1. System architecture

2.3. Control parameters and optimal range

Based on the literature review and the experimental requirements of the hydroponic system, optimal ranges for each monitored environmental parameter were established as references for the automatic control process. These parameters include pH value, TDS concentration, and nutrient solution temperature, as summarized in Table 1 [21], [22]. The pH is maintained at 5.5–6.5 for optimal nutrient uptake, TDS at 560 to 840 ppm for balanced nutrition, and temperature at 18–24 °C to support plant metabolism and system stability. Table 1 defines the control thresholds. When values deviate from optimal limits, the system automatically activates actuators (nutrient, pH, and water pumps, and cooling fans) to restore ideal conditions [23].

Table 1. Optimal ranges of monitored parameters

No	Parameter	Optimal Range
1	pH	5.5 - 6.5
2	TDS	560-840 ppm
3	Temperature	18-24 °C

2.4. Automatic temperature compensation

Temperature affects conductivity and ion mobility, causing deviations in TDS and pH readings. To mitigate this, ATC adjusts measurements based on actual solution temperature, improving accuracy [24]. This enables more precise nutrient and pH control, enhancing system stability and reliability.

2.4.1. Temperature compensation in TDS measurement

TDS measurements are affected by solution temperature; higher temperatures increase conductivity, leading to inflated readings despite unchanged nutrient concentration. Therefore, ATC is required for accurate measurement. The temperature-compensated TDS value is calculated using (1).

$$TDS_{Comp} = \frac{TDS_{raw}}{1+\alpha\,(T-T_{ref})} \quad (1)$$

TDS_{comp} is the temperature-compensated TDS value (ppm), TDS_{raw} is the raw TDS value directly measured by the sensor (ppm), T is the measured temperature of the solution (°C), T_{ref} is the reference temperature used as a standard, set at 25 °C, α is the TDS temperature coefficient with a value of 0.02 per °C. This equation corrects TDS for temperature relative to 25 °C, decreasing values above and increasing values below it, improving accuracy and stability for reliable nutrient control.

2.4.2. Temperature compensation in pH measurement

The pH measurements are affected by temperature, which alters hydrogen ion (H^+) activity and sensor electrode response, reducing accuracy. Therefore, ATC is required to ensure consistent and accurate readings. The temperature-compensated pH value is calculated using (2), as follows:

$$\left(pH_{comp}\right) = pH_{raw} + \beta\,(T_{ref} - T) \tag{2}$$

pH_{comp} is the temperature-compensated pH value, pH_{raw} is the raw pH value directly measured by the pH sensor, T is the measured temperature of the nutrient solution (°C), T_{ref} is the reference temperature used as a standard, set at 25 °C, β is the temperature correction coefficient with a value of 0.03 pH per °C. This equation adjusts pH relative to temperature: lower temperatures increase pH, while higher temperatures decrease it, improving accuracy and stability for optimal nutrient control.

2.5. System control algorithm for SMAC

The system uses a threshold-based control algorithm to maintain pH, TDS, and temperature within optimal ranges, as illustrated in Figure 2. The system samples pH, TDS, and temperature every 5 seconds and applies ATC for accurate readings. If temperature exceeds safe limits, a safety lock disables all actuators. Otherwise, pH is adjusted via pH Up/Down pumps, and TDS is controlled using the nutrient pump (<560 ppm) or Aquades (distilled water) pump (>840 ppm). All data and actuator statuses are transmitted to the IoT platform for real-time monitoring, ensuring stable and reliable control.

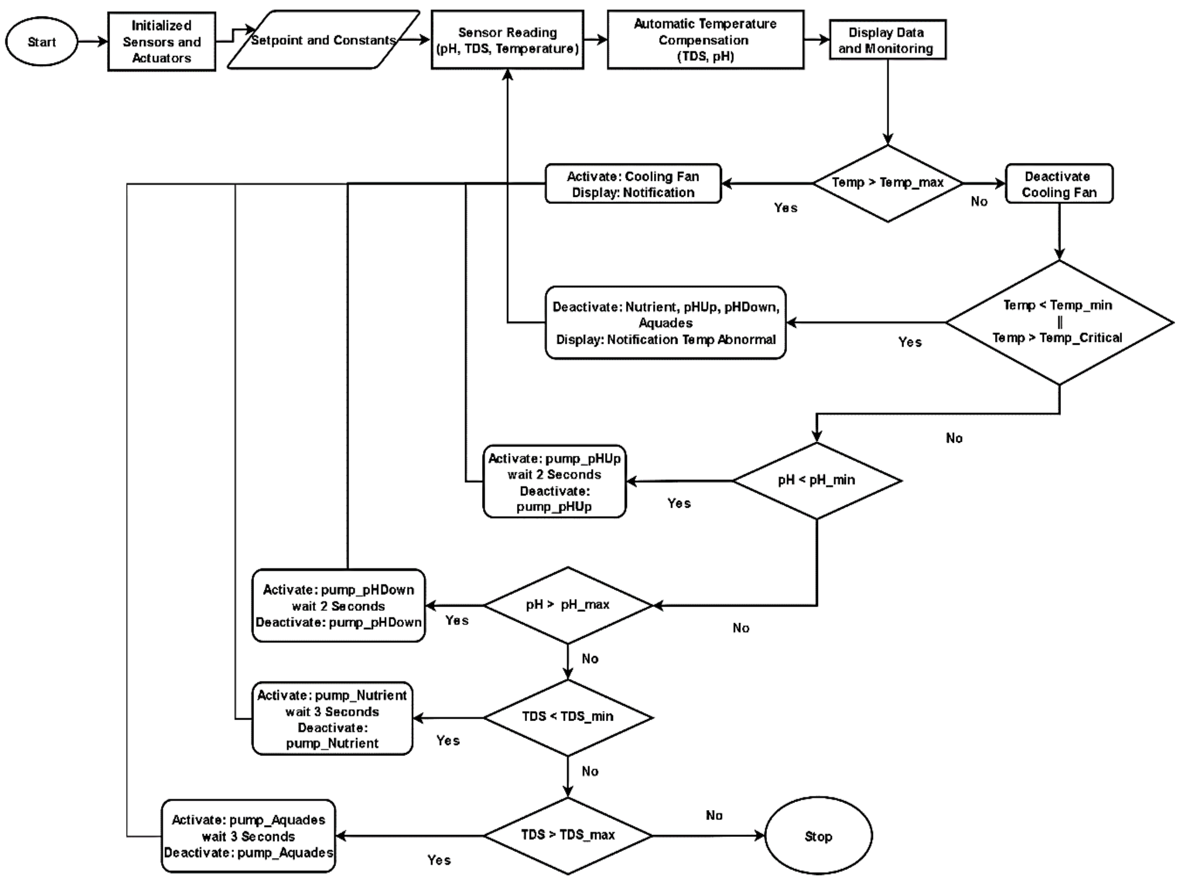

Figure 2. Flowchart system for SMAC

2.6. Experimental setup

The SMAC system was evaluated using a laboratory-scale NFT hydroponic setup equipped with pH, TDS, and temperature sensors, together with nutrient, pH Up, pH Down [25], and Aquades pumps, as well as a cooling fan. Sensor readings were collected every 5 seconds, processed through the ATC mechanism, and used to trigger actuator responses based on predefined control rules. The system operated with a dual-microcontroller configuration, where the Arduino Uno handled sensing and actuation while the ESP32 managed IoT communication. The experiment was conducted over a 3-hour continuous testing period, during which three categories of tests were performed. First, sensor accuracy was validated across temperatures of 20–27 °C, with five measurement repetitions at each temperature point. Second, system responsiveness was assessed through controlled disturbances: solution temperature was raised above 24 °C, pH was shifted outside the 5.5–6.5 range, and TDS was varied beyond 560–840 ppm by adding either nutrient solution or Aquades. Each disturbance scenario was executed in three independent trials to ensure repeatability. Finally, an uninterrupted operation test was carried out to observe actuator reliability, sensor stability, and IoT communication performance throughout the full duration. All raw and ATC-corrected sensor data, along with actuator states, were transmitted to the IoT dashboard for real-time monitoring and logged for subsequent analysis. These data were used to evaluate the stability, responsiveness, and overall conformity of the system with the designed control algorithm.

3. RESULTS AND DISCUSSION

3.1. Hardware and software implementation

The system was implemented by integrating hardware and software and tested on a laboratory-scale hydroponic setup with standard nutrient solution. Figure 3 shows the real-time monitoring system displaying pH, TDS, and temperature with timestamps for direct observation of operating conditions. The system includes a data history feature as shown in Figure 3, for analyzing trends, stability, and control performance, with IoT integration enabling remote monitoring. Hardware components are housed in a wooden enclosure for protection and efficient layout. The NFT-based setup comprises planting channels, a reservoir, a pump, and a support frame, enabling continuous nutrient flow, efficient resource use, and scalable application.

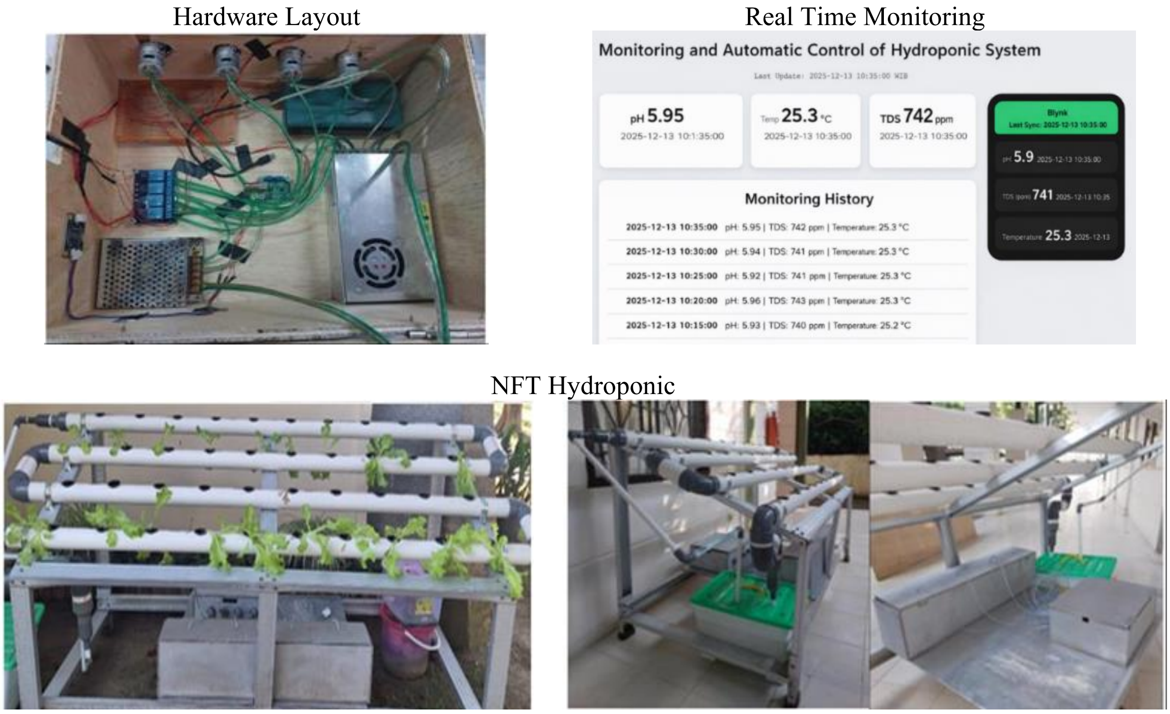

Figure 3. Implementation

3.2. Testing and analysis of results

System testing evaluated sensor accuracy, actuator response, control stability, and the reliability of the IoT-based monitoring system in line with the implemented algorithm.

3.2.1. Sensor accuracy testing

Sensor accuracy was evaluated by comparing pH, TDS, and temperature readings with standard instruments. Both raw and ATC-compensated data were analyzed to verify improved stability and closer agreement with reference values.

Table 2 shows raw pH deviations from reference values when temperature differs from 25 °C, with errors up to 0.40 (highest at 20 °C). Higher temperatures decrease pH readings, while lower temperatures increase them. ATC reduces temperature effects, achieving zero error at 25 °C and low error at 24 °C (0.13), but larger errors at extremes (20 °C: 0.55; 27 °C: 0.26), reflecting limits of the linear model (β = 0.03 pH/°C). Although average ATC error (0.23) slightly exceeds raw error (0.17), it improves stability and reduces incorrect control actions.

Table 2. pH sensor accuracy testing with and without ATC

No	Temperature (°C)	pH Reference	pH Raw	Error Raw	pH ATC	Error ATC
1	20	6.5	6.9	0.40	7.06	0.55
2	22	6.5	6.7	0.20	6.79	0.29
3	24	6.5	6.6	0.10	6.63	0.13
4	25	6.5	6.5	0.00	6.50	0.00
5	26	6.5	6.4	0.10	6.37	0.13
6	27	6.5	6.3	0.20	6.24	0.26

Table 3 shows that temperature significantly affects TDS measurements (20–27 °C, 800 ppm reference), with raw errors of 20–100 ppm, highest at 20 °C. ATC improves accuracy near 25 °C, achieving a minimum error of 4.1 ppm at 24 °C, but errors increase at extremes (20 °C: 200 ppm; 27 °C: 107.7 ppm), reflecting limits of the linear model (α = 0.02). Despite this, ATC stabilizes measurements and improves control consistency.

Table 3. TDS sensor accuracy testing with and without ATC

No	Temperature (°C)	TDS Reference (ppm)	TDS Raw (ppm)	Error Raw	TDS ATC (ppm)	Error ATC
1	20	800	900	100	1000	200
2	22	800	840	40	893.6	93.6
3	24	800	780	20	795.9	4.1
4	25	800	760	40	760	40
5	26	800	740	60	725.5	74.5
6	27	800	720	80	692.3	107.7

Based on the test results presented in Table 4, the temperature sensor readings show good agreement with the reference digital thermometer over the temperature range of 20–27 °C. The absolute reading difference (absolute error) ranges from 0.0 to 0.2 °C, indicating a high level of accuracy and stability of the temperature sensor. When evaluated in terms of percentage error, the relative error was calculated using (3):

$$Percentage\ Error = \frac{|Sensor - Reference|}{Reference}\ x\ 100\% \quad (3)$$

Table 4. Temperature sensor accuracy testing

No	Reference Thermometer (°C)	Temperature Sensor (°C)	Error Absolut (°C)	Percent Error (%)
1	20.0	20.2	0.2	1.00
2	22.0	22.1	0.1	0.45
3	24.0	24.2	0.2	0.83
4	25.0	25.0	0.0	0.00
5	26.0	26.1	0.1	0.38
6	27.0	27.2	0.2	0.74

The temperature sensor shows 0.0–1.0% error, with a maximum of 1.0% (0.2 °C) at 20 °C and zero error at 25 °C. The average error is ~0.5%, with an absolute error of 0.13 °C and a standard deviation of 0.07 °C, indicating low variability and stable performance. High accuracy at 25 °C supports reliable ATC, confirming suitability for hydroponic control.

3.2.2. System response testing to non-ideal conditions

Testing involved varying nutrient conditions to evaluate system response. pH and TDS were set beyond thresholds to trigger pH Up/Down, nutrient, and dilution pumps. Performance was assessed based on ATC-compensated readings, pump activation, operation time, and resulting pH and TDS changes.

Table 5 shows that a 2 seconds pH Up pump cycle increases pH by 0.18–0.52 (avg. ~0.31) per activation. This provides fast, controlled correction with minimal overshoot, confirming the effectiveness of the pH control strategy for maintaining system stability. Table 6 shows that a 2 seconds pH down pump cycle reduces pH by 0.28–0.45 (avg. ~0.38) per activation. This provides fast, controlled correction with minimal overshoot and oscillation, confirming effective and stable pH regulation.

Figure 4 shows stable, automatic pH control: the pH up pump raises low pH and the pH down pump reduces high pH, both without overshoot or oscillation. The threshold-based strategy provides fast, stable, and adaptive regulation, confirming its suitability for IoT-based hydroponic systems.

Table 5. System response testing to low pH (pH up pump activation)

No	Initial pH ATC	pH Limit	Pump Active	Duration (seconds)	Final pH ATC	System Response
1	5.20	5.5 – 6.5	pH Up	2	5.48	Increases pH
2	5.10	5.5 – 6.5	pH Up	2	5.62	Normal
3	5.30	5.5 – 6.5	pH Up	2	5.55	Normal
4	5.40	5.5 – 6.5	pH Up	2	5.58	Normal
5	5.60	5.5 – 6.5	–	–	5.60	Stable

Table 6. System response testing to high pH (pH down pump activation)

No	Initial pH ATC	pH Limit	Pump Active	Duration (seconds)	Final pH ATC	System Response
1	6.80	5.5 – 6.5	pH Down	2	6.52	Decrease pH
2	6.90	5.5 – 6.5	pH Down	2	6.45	Normal
3	7.00	5.5 – 6.5	pH Down	2	6.60	Approaching the limit
4	6.70	5.5 – 6.5	pH Down	2	6.48	Normal
5	6.40	5.5 – 6.5	–	–	6.40	Stable

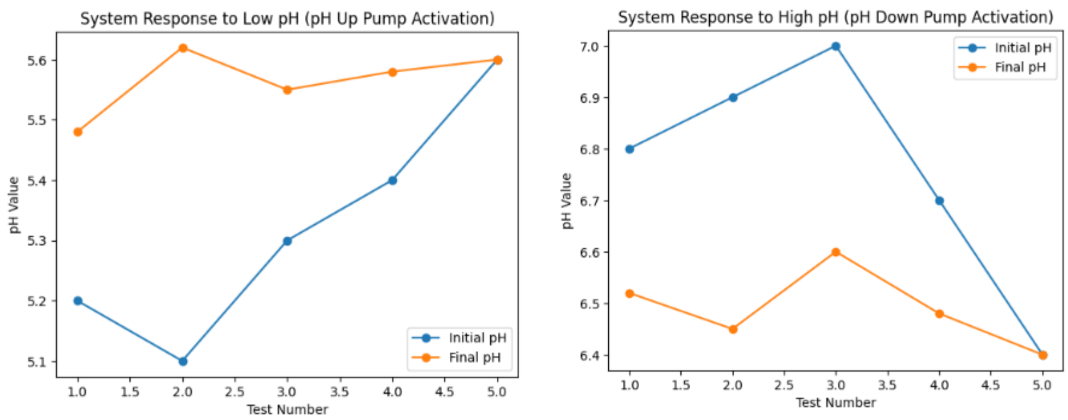

Figure 4. System response graph for low pH and high pH

Evaluations under low TDS conditions show stable and effective control, as shown in Table 7. The system detects deficiencies and activates the nutrient pump to restore TDS without overshoot. A 3 s cycle increases TDS by ~75 ppm (~25 ppm/s) with low variation, indicating consistent and predictable performance. Overall, the strategy supports reliable and continuous nutrient control.

Table 7. System response testing to low TDS (nutrient pump activation)

No	Initial TDS ATC (ppm)	TDS Limit (ppm)	Pump Active	Duration (seconds)	Final TDS ATC (ppm)	System Response
1	480	560 – 840	Nutrient	3	540	Increase TDS
2	500	560 – 840	Nutrient	3	580	Normal
3	520	560 – 840	Nutrient	3	600	Normal
4	550	560 – 840	Nutrient	3	630	Normal
5	600	560 – 840	–	–	600	Stable

Table 8 shows that when TDS exceeds 840 ppm, the system activates the Aquades pump for gradual dilution. For high initial values (*e.g.*, 900 ppm), a 3 s cycle reduces TDS incrementally without overshoot, while values near the threshold (850–880 ppm) return to the optimal range in one cycle. Overall, the control is stable and effective.

Table 8. System response testing to high TDS (Aquades pump activation)

No	Initial TDS ATC (ppm)	TDS Limit (ppm)	Pump Active	Duration (seconds)	Final TDS ATC (ppm)	System Response
1	900	560 – 840	Aquades	3	860	TDS Decreases
2	880	560 – 840	Aquades	3	830	Normal
3	860	560 – 840	Aquades	3	800	Normal
4	850	560 – 840	Aquades	3	820	Normal
5	800	560 – 840	–	–	800	Stable

3.2.3. pH and TDS stability testing

Stability testing evaluated the system's ability to maintain pH (5.5–6.5) and TDS (560–840 ppm). Proper operation is achieved when values return to range after several corrections without excessive oscillation. Table 9 shows effective stabilization from out-of-range conditions (pH 5.20; TDS 900 ppm). The system applies incremental corrections (within 10 s: pH 5.60; TDS 830 ppm), avoiding oscillations. Once within range, pH remains at 5.8–6.1 and TDS at 760–800 ppm with minor fluctuations. This confirms stable, reliable control supported by appropriate sampling, actuation, and ATC.

Table 9. Results of pH and TDS stability tests over time

No	Time (Seconds)	pH ATC	Status pH	TDS ATC (ppm)	Status TDS
1	0	5.20	Unstable	900	Unstable
2	5	5.40	Approaching the limit	860	Decreasing
3	10	5.60	Normal	830	Normal
4	15	5.80	Normal	800	Normal
5	20	6.00	Normal	780	Normal
6	25	6.10	Normal	760	Normal
7	30	6.00	Normal	770	Normal
8	35	5.90	Normal	780	Normal

Figure 5 shows effective TDS control within 560–840 ppm. The system increases TDS via the nutrient pump when below the threshold and decreases it via the Aquades pump when above it. No action is taken within range, ensuring stable and reliable operation. Figure 6 shows the system correcting low pH and high TDS to optimal ranges. pH stabilizes at 5.8–6.1 and TDS at 760–830 ppm, with only minor fluctuations and no significant oscillations. This confirms stable, coordinated, and effective control.

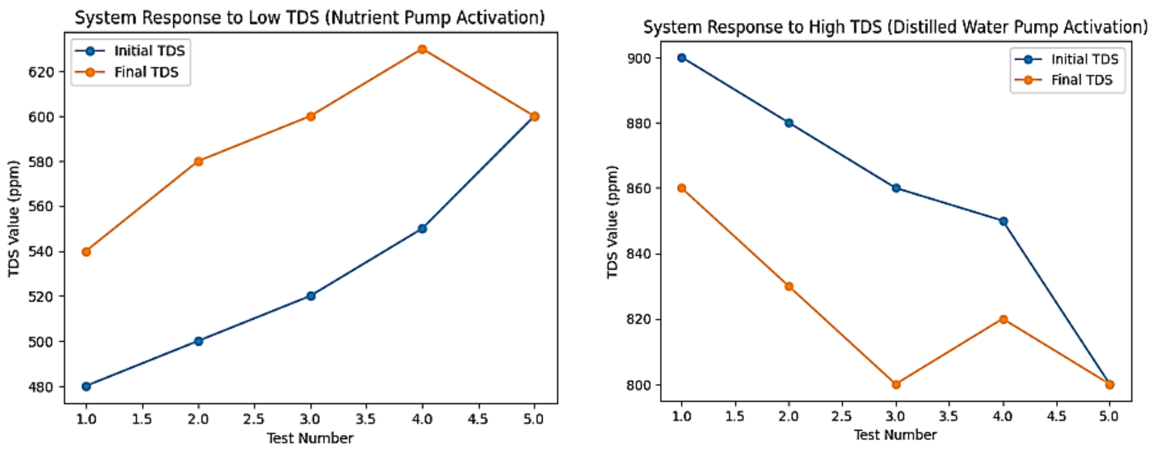

Figure 5. Graph of response low and high TDS

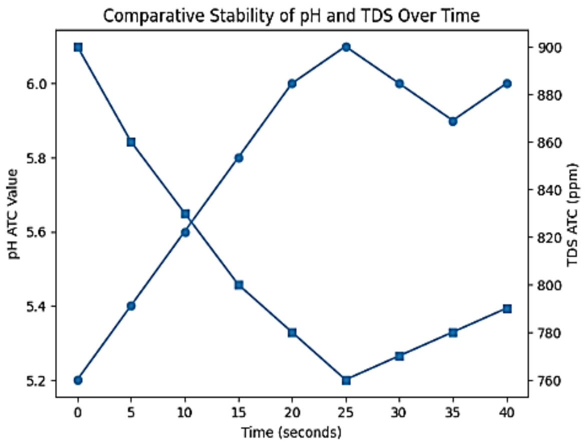

Figure 6. Graph of comparative stability pH and TDS

3.2.4. Temperature control and safety lock testing

Temperature was varied to evaluate system response. The cooling fan activated above 24 °C, and at extreme levels (>28 °C), a safety lock disabled all actuators, placing the system in a hold state. Table 10 confirms effective temperature control and safety. At 18–24 °C, all actuators operate normally with the cooling fan off. Above 24 °C, the fan activates without interrupting control. At ≥28 °C, a safety lock disables all pumps while monitoring continues, and normal operation resumes once temperature stabilizes.

Table 10. Hydroponic system temperature control and safety lock test results

No	Solution Temperature	Temp Limit	Condition	Fan	Nutrition	pH	Aquades	Description
1	20(°C)	18 – 24	Normal	OFF	Auto	Auto	Auto	Normal
2	23(°C)	18 – 24	Normal	OFF	Auto	Auto	Auto	Optimal
3	25(°C)	> 24	Warning	ON	ON	ON	ON	Cooling ON
4	26(°C)	> 24	Warning	ON	ON	ON	ON	Cooling ON
5	27(°C)	> 24	Warning	ON	ON	ON	ON	Cooling ON
6	28(°C)	≥ 28 (Critical)	Hold	ON	OFF	OFF	OFF	All OFF
7	29(°C)	≥ 28 (Critical)	Hold	ON	OFF	OFF	OFF	All OFF
8	24(°C)	18 – 24	Normal	OFF	Auto	Auto	Auto	Normalized

3.2.5. IoT system reliability testing

IoT reliability was evaluated by monitoring real-time data transmission to the Blynk app, focusing on delay, connection stability, and consistency between displayed and actual system data. Table 11 shows reliable real-time IoT monitoring via Blynk. Data were transmitted every 5 s with low delays (0.8–1.1 s) during normal operation and slightly higher delays (1.1–1.2 s) under abnormal conditions, maintaining system observability. Under unstable networks, delays rose to ~2.5 s, but automatic reconnection ensured continuity. Overall, the system provides reliable and resilient monitoring without affecting control stability.

Table 11. IoT system reliability test results (Blynk)

No	Condition	Data Sent	Interval (S)	Delay (S)	Status	Data Sync	Description
1	Normal (pH & TDS Stable)	pH, TDS, ATC, Temperature	5	0.8	Stable	Sync	Real-time OK
2	pH < Min	pH, ATC, pHUp	5	0.9	Stable	Sync	Pump Shown
3	pH > Max	pH, ATC, pHDown	5	0.9	Stable	Sync	System Response
4	TDS < Min	TDS, ATC, Nutrient	5	1.0	Stable	Sync	Correction active
5	TDS > Max	TDS, ATC, Aquades	5	1.1	Stable	Sync	Dilution visible
6	Temp > Max	Temp, Fan	5	1.0	Stable	Sync	Warning Shown
7	Temp ≥ Critical	Temp, Hold	5	12	Stable	Sync	Safety lock
8	Network Unstable	Last Data + Reconnect	5	2.5	Disconnected	Sync after reconnect	Recovered

3.2.6. Monitoring history testing

Table 12 shows stable real-time monitoring, with pH ranging from 5.92 to 5.96, indicating well-controlled acidity and effective detection of minor variations. TDS remained stable at 740–744 ppm with no significant spikes, indicating consistent monitoring. Temperature varied slightly (25.1–25.3 °C), showing stable conditions and minimal impact on pH and TDS, while confirming sensor reliability. Overall, Table 12 demonstrates effective real-time monitoring and stable parameter control.

Table 12. History data monitoring dashboard

No	Time	pH	TDS (ppm)	Temperature (°C)
1	10:00	5.93	740	25.1
2	10:05	5.94	742	25.2
3	10:10	5.92	741	25.3
4	10:15	5.95	743	25.3
5	10:20	5.93	740	25.2
6	10:25	5.94	741	25.2
7	10:30	5.96	744	25.3
8	10:35	5.95	742	25.3

4. CONCLUSION

This study developed and evaluated an IoT-based SMAC framework for an NFT hydroponic system, integrating real-time sensing, automatic actuation, and temperature-aware decision-making into a closed-loop control architecture. The system regulates pH, TDS, and temperature using ATC-corrected measurements, ensuring more accurate and stable control compared to conventional threshold-based or monitoring-only IoT systems.

The main contributions of this work can be summarized as follows: Development of a dual-microcontroller IoT control system that separates real-time sensing/actuation (Arduino Uno) from wireless communication (ESP32), improving reliability and modularity. Integration of an ATC mechanism directly into the pH and TDS control logic, enabling temperature-aware decision-making. Implementation and experimental validation of a closed-loop control algorithm capable of restoring pH and TDS to optimal ranges without oscillation under both steady and disturbed conditions. Design of a safety-lock mechanism that enhances operational reliability when abnormal temperature conditions occur.

The SMAC system reduces labor, minimizes human error, and ensures consistent nutrient management, supporting precision and sustainable hydroponics. IoT monitoring enables remote supervision, making it suitable for small- to medium-scale use. Limitations include the NFT setup, a linear ATC model, and focus on control performance rather than plant growth. Future work will extend to other systems, integrate cloud analytics and AI-based control, and include field and yield evaluations. Overall, SMAC offers a robust and scalable solution for automated hydroponic management.

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AUTHOR CONTRIBUTIONS STATEMENT

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Marojahan Mula				✓		✓						✓		✓
Timbul Sigiro														
Gerry Italiano Wowiling				✓		✓	✓					✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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