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Design of IoT-Based Smart Hydroponic Farming with Solar Energy for Sustainable and Precision Crop Production

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Abstract

Conventional hydroponic farming systems frequently encounter limitations related to unstable environmental control, suboptimal nutrient management, and strong dependence on grid-based electricity, which collectively hinder their sustainability and scalability, particularly in remote or energy-constrained regions. Recent studies have explored smart hydroponic technologies. However, many remain reliant on external power sources or lack integrated, autonomous control of multiple critical growth parameters. Therefore, this problem reveals a research gap in the development of fully self-powered and intelligent hydroponic systems. This study proposes the design and implementation of a solar-powered, IoT-based smart hydroponic farming system that enables real-time monitoring and closed-loop environmental control. The system integrates multi-sensor measurements, including pH, DS18B20 temperature, total dissolved solids (TDS), and light-dependent resistor (LDR) sensors, coupled with an on–off control strategy to regulate light intensity (115 ADC), water temperature (28 °C), pH (5.5-6.5), and nutrient concentration (840 ppm). A standalone photovoltaic energy subsystem, consisting of a 100 Wp solar panel and a 65 Ah battery, was designed based on a daily energy demand of 378.85 Wh to ensure continuous autonomous operation. Experimental results demonstrate high sensor accuracy, with measurement errors of 0.75% for pH, 0.095% for TDS, and 0.24% for temperature. Moreover, the proposed system effectively stabilizes environmental parameters within predefined setpoints, outperforming uncontrolled conditions. These findings confirm the system's reliability and potential as a sustainable precision agriculture solution for off-grid hydroponic applications.

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1. Introduction

Hydroponic farming has emerged as a modern agricultural approach capable of improving food productivity while reducing water consumption and dependency on fertile land, making it highly relevant for urban cultivation and climate-affected regions [1]. To achieve optimal crop growth, hydroponic systems require precision control of critical environmental parameters such as nutrient concentration, pH level, temperature, humidity, and light intensity, which is difficult to maintain under manual operation [2]. Meanwhile, the increasing demand for sustainable agriculture encourages the adoption of low-carbon technologies, including renewable energy sources, to reduce reliance on conventional electricity and operational costs [3]. However, many existing hydroponic implementations still face challenges such as limited real-time monitoring, inconsistent decision-making, and unstable energy availability, resulting in suboptimal crop yield and system reliability [4]. These challenges highlight the urgent need for an intelligent, energy-independent hydroponic system capable of ensuring continuous monitoring, precise environmental control, and sustainable operation to support reliable and high-quality crop production [5].

Previous research has demonstrated multiple innovations toward smart hydroponic automation, such as IoT enabled EC and pH control systems that regulate nutrient dosing using peristaltic pumps and live sensor feedback to maintain optimal plant growth thresholds [6]. Other studies developed cloud-connected dashboards to provide historical data visualization and remote supervision of lettuce and tomato production inside controlled environments [7]. Other research has developed an IoT-based, solar-powered, and extreme environment-resistant shallot irrigation and monitoring system, proven to maintain optimal soil moisture, increase water efficiency, and support sustainable cultivation in remote areas [8]. In addition, IoT and solar power are capable of monitoring battery capacity and gas concentration in real-time, increasing operating duration and speeding up the field inspection process [9]. In precision control, intelligent decision-making methods such as fuzzy logic for nutrient balancing, PID-based irrigation scheduling, and machine-learning-driven environmental prediction have been deployed to reduce manual intervention and increase crop uniformity [10], [11]. Meanwhile, optimization of growing parameters using reinforcement learning and digital-twin climate simulation has begun to show potential in minimizing energy and water waste while improving nutrient uptake efficiency [12].

To address sustainability concerns, several studies have introduced standalone photovoltaic (PV) power systems to stabilize hydroponic operations in remote or grid-limited areas, where PLTS-supported greenhouses were shown to maintain irrigation and sensor communication with reduced carbon footprint [13]. PV battery hybrids have also been integrated with hydroponic control units to enable uninterrupted automation during nighttime operation and cloudy weather conditions [14]. In addition, recent prototypes incorporated MPPT-based solar charging, wireless sensor networks, and mobile-based alert systems into a single platform, increasing system mobility and long-term feasibility for small-scale farmers [15], [16]. Despite these advancements, most prior systems remain limited to either monitoring only (without adaptive control), energy supply only (without intelligent nutrient regulation), or local logging only (without IoT based decision support). Furthermore, several studies reported practical constraints such as unstable connectivity, uneven power distribution, time lagged responses to environmental changes, and the absence of integrated automation that simultaneously manages nutrient solution, climate variables, irrigation cycles, and PV energy consumption in real-world operations [17]. However, many remain reliant on external power sources or lack integrated, autonomous control of multiple critical growth parameters.

This study addresses these challenges by proposing a holistic IoT-driven smart hydroponic automation system powered by solar energy. It is designed to provide real-time sensing, autonomously optimize critical growing parameters, and ensure energy-efficient continuous operation. The proposed system integrates an IoT-based monitoring and control framework capable of regulating nutrient concentration, pH level, temperature, humidity, and light intensity to support precision crop production. A solar energy–based power management subsystem is incorporated to ensure reliable and sustainable operation, particularly in environments with limited access to conventional electrical grids. Furthermore, a decision-making algorithm is implemented to autonomously optimize growing conditions based on real-time sensor feedback, thereby enhancing crop consistency while minimizing human intervention. The system is experimentally evaluated under real cultivation conditions, and its performance is analyzed in terms of operational reliability, environmental stability, and productivity improvement in hydroponic lettuce production. The remainder of this article presents the system architecture and methodology, followed by experimental results and discussion, and concludes with key findings and future research directions.

2. Research Methodology

2.1. System Architecture

Figure 1 presents the system architecture of the proposed IoT-based smart hydroponic solution powered by solar photovoltaic (PV) energy. The architecture is composed of three main subsystems: (1) sensor unit, (2) control and power management unit, and (3) actuator unit interconnected via an IoT communication layer.

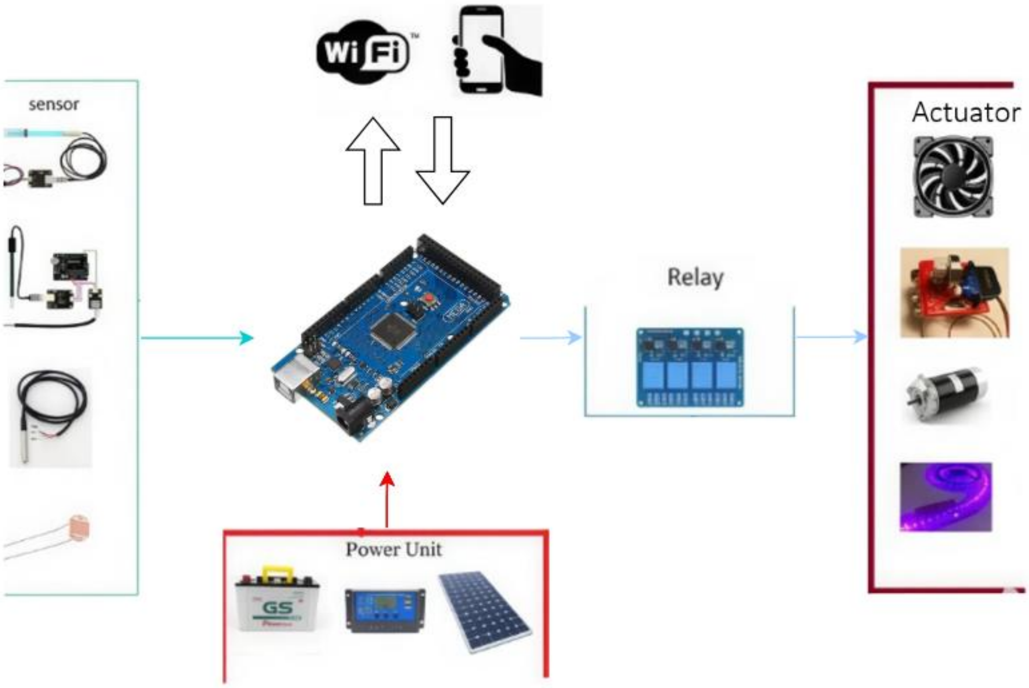

Figure 1. The System Architecture of The Proposed Iot Based Smart Hydroponic with PV Energi

The sensor unit consists of four real-time monitoring devices, namely: pH sensor, temperature sensor, light-dependent resistor (LDR) sensor, and TDS/PPM sensor. These sensors continuously acquire data regarding nutrient concentration, environmental temperature, surrounding light intensity, and water quality parameters, which are then transmitted to the microcontroller for processing. The control and power management unit utilizes an Arduino-based microcontroller as the central decision-making module. A closed-loop on–off control strategy is implemented to maintain each environmental parameter within its optimal threshold range. The microcontroller evaluates measured feedback against predefined setpoints and activates actuators only when deviations exceed allowable tolerance, ensuring both system stability and energy efficiency. A relay driver module is embedded to provide electrical isolation and secure switching for all controlled devices. Additionally, a solar PV panel complemented by a charge controller and battery storage system supplies uninterrupted and eco-efficient power to the entire installation, supporting continuous operation even under limited grid availability.

The actuator unit comprises several automated components: a DC water pump for nutrient circulation, a servo-driven valve for precise pH-up and pH-down dosing, ventilation fans for micro-climate regulation, UV-based grow lights to support continuous and optimal photosynthesis, and a DC motor for nutrient solution flow management. These actuators are controlled based on continuous sensor feedback through a closed loop on off control mechanism, ensuring that pH balance, nutrient concentration, temperature, and light exposure remain within their optimal zones for healthy plant metabolism. The availability of grow lights enables plants to maintain uninterrupted photosynthetic activity, even under low-sunlight conditions, thereby preventing growth inhibition, ensuring consistent biomass formation, and improving overall crop productivity. Moreover, the system integrates a Wi-Fi communication interface providing remote accessibility through a smartphone-based monitoring application. Users can observe real-time sensor data, receive alert notifications, and optionally override automatic commands, thereby enhancing user involvement and supporting scalability in modern precision agriculture.

Meanwhile, the operational workflow of Iot Based Smart Hydroponic with PV Energy represented in the flowchart shown in Figure 2. In this architecture, the microcontroller continuously receives feedback from four primary sensors: pH sensor, water temperature sensor, LDR light intensity sensor, and TDS/PPM sensor for nutrient concentration monitoring.

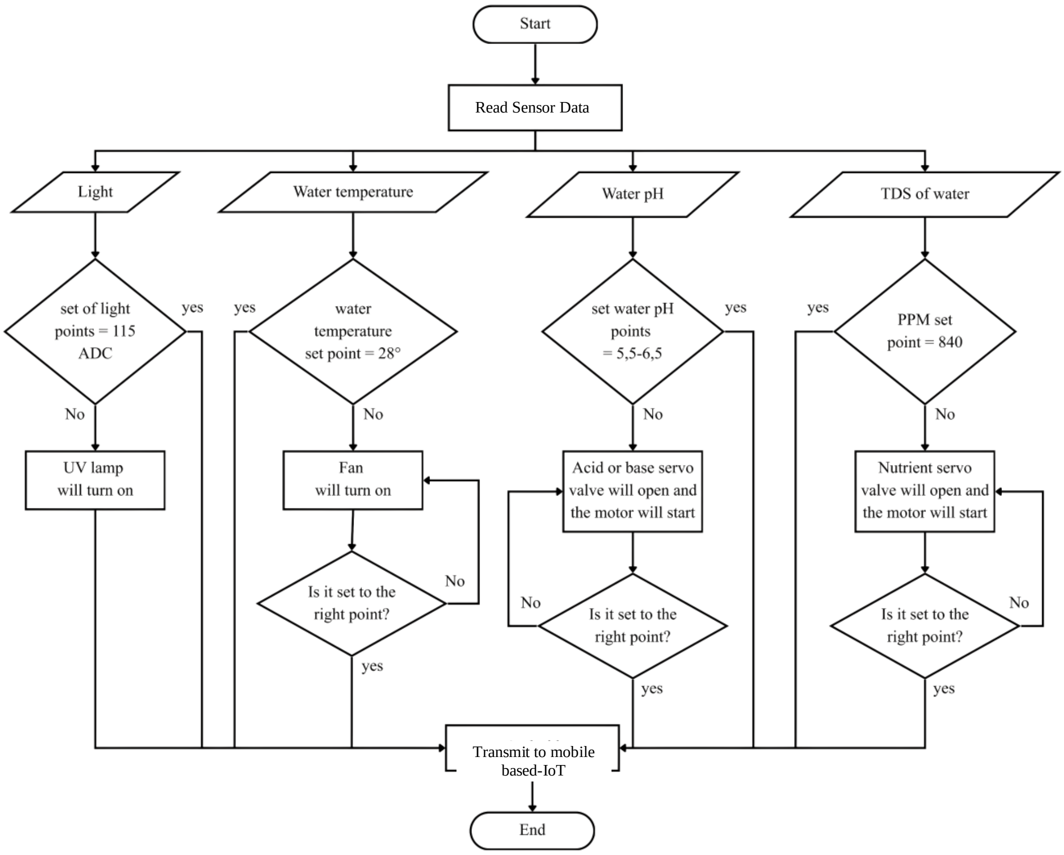

Figure 2. Workflow of IoT Based Smart Hydroponic with PV Energi

Each measured parameter is evaluated against predefined set points, namely 115 ADC for light intensity, 28 °C for water temperature, pH range of 5.5–6.5, and 840 ppm for nutrient concentration. When the measured value deviates from its set point, the system automatically triggers the corresponding actuator to perform corrective actions. For light regulation, when the LDR value falls below the light threshold, the UV lamp is activated to maintain adequate illumination for optimal photosynthesis. Temperature control is carried out by a cooling fan, which operates whenever the temperature exceeds the defined set point and stops once it returns to normal. In the pH-control loop, if the real-time pH value lies outside the optimal range, the system actuates servo valves to dispense either pH-up or pH-down solution, assisted by a solution pump, until the pH returns to the target range. Likewise, nutrient regulation is managed by the nutrient servo valve and nutrient pump, which are activated to increase nutrient concentration when the TDS value falls below the set point.

All actuation processes operate in a closed loop feedback mechanism, in which each actuator will automatically deactivate once the parameter is restored to its desired set point. In addition, all monitoring data and actuator statuses are transmitted in real-time via a Wi Fi communication interface to an Android-based smartphone application, enabling remote supervision, system alerts, and manual override when required. Through this integrated loop of sensing, processing, actuation, and wireless control, the system ensures environmental stability, energy-efficient operation, and reliable crop growth performance in modern hydroponic farming.

Table 1. Electrical Load Calculation of the Smart Hidroponic System

Equipment	Quantity (units)	Operating Voltage (VDC)	Operating Current (A)	Operating Time (h)	Energy Consumption (Wh) *(P = n × W × h)*
Water Pump	1	12	0.7	24	201.6
Servo Valve	4	5	1.1	1	22.0
UV Lamp	1	12	0.6	10	72.0
Microcontroller	1	5	0.1	24	12.0
DC Motor	1	12	1.7	1	20.4
Cooling Fan	1	12	0.12	1	1.44
Total Energy Consumption					329.44 Wh/day

2.2. Solar Photovoltaic Design

Load calculation represents the initial and fundamental step in designing the power supply system to ensure that the overall smart hydroponic system operates effectively and efficiently. In this study, the load calculation is performed based on the electrical power requirements and technical specifications of all equipment utilized in the system, including sensors, microcontroller, communication modules, actuators, and lighting units. Each component is evaluated in terms of its rated voltage, current, power consumption, and operational duration to estimate the total daily energy demand. The detailed results of this load calculation are summarized in Table 1, which serve as the primary reference for determining the appropriate capacity of the solar photovoltaic panel, charge controller, battery storage, and overall power distribution architecture. By accurately defining the total energy requirement of the smart hydroponic system, the proposed solar-powered design can ensure reliable continuous operation, optimal energy utilization, and long-term system sustainability.

Based on the electrical load analysis summarized in Table 1, which presents the power consumption and operating duration of each component in the smart hydroponic automation system, the total net daily energy demand was first obtained as $E_A = 329.44$. The total required system energy was then determined by accounting for estimated system losses according to the relation:

$$E_T = E_A + \text{system losses} = E_A + (0.15 \times E_A) \tag{1}$$

Substituting the computed net energy demand yields:

$$E_T = 329.44 + (0.15 \times 329.44\,)$$
$$= 329.44\ + 49.41$$
$$= 378.85\ \text{Wh}$$

Here, E_T denotes the total daily energy requirement inclusive of estimated losses, and E_A denotes the total daily energy requirement exclusive of losses. Therefore, the overall energy demand for the smart hydroponic automation system is established as **378.85 Wh per day**, which serves as the primary design basis for sizing the solar photovoltaic module, battery capacity, and charge controller.

The required power capacity of the solar photovoltaic module was determined based on the total daily energy demand of the system, $E_T = 378.85$, as previously obtained. The solar module capacity was calculated using the relation:

$$P_{PV} = \frac{378.85}{4.4} \times 1.1 = 82.36\ \text{Wp} \tag{2}$$

Thus, the theoretical photovoltaic module capacity required to supply the smart hydroponic automation system is 82.36 watt-peak (Wp). Considering standard commercial PV module ratings and practical design margins, the system is configured using a 100 Wp solar module with an estimated efficiency of 85%. This oversizing strategy ensures reliable energy availability under non-ideal environmental conditions such as cloud cover, temperature variations, and partial shading.

After determining the PV module capacity, the next design step involves calculating the required battery capacity to store sufficient electrical energy for uninterrupted system operation. The battery capacity is obtained by converting the total energy demand from watt-hours (Wh) to ampere-hours (Ah) using the relation:

$$AH = \frac{E_T}{V_s} = \frac{378.85}{12} = 31.57\ \text{Ah} \tag{3}$$

where AH represents the required battery capacity, E_T denotes the total energy requirement including system losses, and V_s is the battery nominal voltage. Based on this calculation, the minimum required battery capacity for the smart hydroponic automation system is 31.57 Ah. To provide operational robustness and sufficient autonomy under non-ideal solar conditions, a 65 Ah battery is selected for the implemented system. It should be noted that these calculations represent ideal conditions assuming optimal solar irradiation; therefore, the selection of higher PV and battery capacities ensures stable and continuous system performance in real operational environments.

Figure 3. Mechanical and Hardware of Hydroponic System

3. Results and Discussions

3.1. Mechanical and Hardware Results

This study successfully developed a compact and solar powered hydroponic system, as shown in Figure 3. The prototype consists of a two-tier plant cultivation structure constructed from lightweight PVC pipe and supported by a corrosion-resistant frame, making it suitable for outdoor balconies or limited-space environments. Lettuce (Lactuca sativa L.) is cultivated in perforated planting tubes with a continuous nutrient flow driven by a DC pump. The system integrates multiple electronic modules, including a microcontroller unit, pH, TDS (ppm), water temperature, and light sensors, along with actuator components such as nutrient dosing valves, a water-cooling fan, and a UV grow light. All components are mounted on a dedicated control board positioned on the front panel of the structure for easy wiring access, maintenance, and monitoring. To enhance sustainability, the entire system is powered by a photovoltaic (PV) panel combined with a battery storage module, enabling autonomous operation with minimal dependence on the main electrical grid.

3.3. PH Sensor Testing

The pH sensor testing was carried out by immersing the pH probe into a standard buffer solution with a nominal value of pH 6.86. The experiment was conducted for a total duration of one minute (60 seconds) with a data acquisition interval of 1 second. During the test, two parameters were simultaneously recorded, namely the measured pH value displayed by the system and the corresponding output voltage generated by the sensor. These data were used to observe the sensor response under a near-neutral reference condition. The detailed results of the pH sensor test using the pH 6.86 buffer solution are presented in the following Figure 4. Based on the pH sensor test using a pH 6.86 buffer solution, the results indicate that the sensor measurement achieved an accuracy of 99.25%, with a relatively small measurement error of 0.75% with respect to the reference pH value of 6.86. This result demonstrates that the pH sensor provides reliable and precise readings under near-neutral conditions.

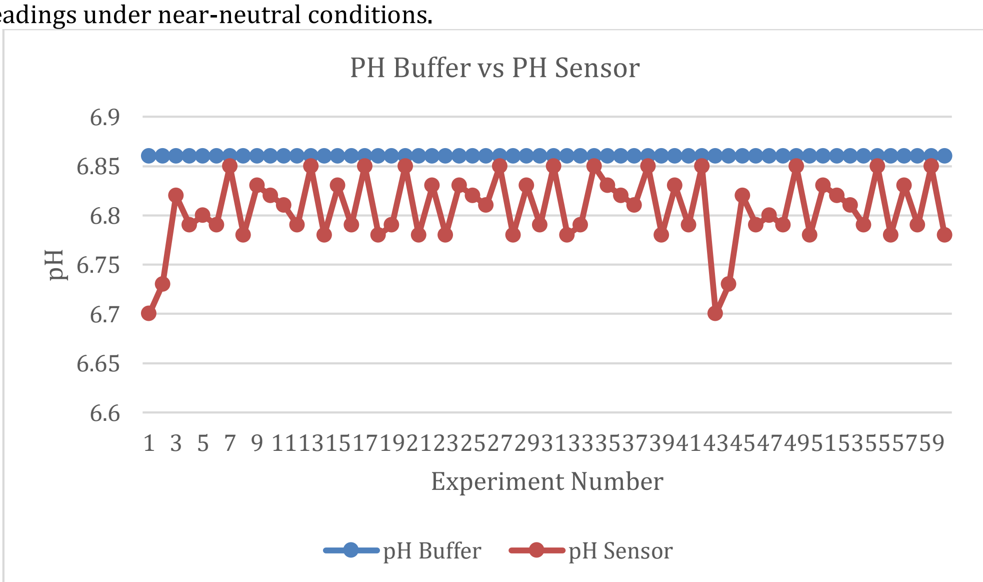

Figure 4. PH Sensor Testing

Table 2. Temperature Sensor Testing Data

Reference Temperature (^{0}C)	Measured Temperature (^{0}C)	Error (%)
30	29.80	0.6667
40	39.80	0.5000
50	49.90	0.2000
60	59.90	0.1667
70	70.00	0.0000
80	79.80	0.2500
90	89.90	0.1111
100	100.00	0.0000
Average Error		0.24

3.4. DS18B20 Temperature Sensor Testing

The DS18B20 temperature sensor was tested by applying controlled heat to the sensor using a heater, with the test temperature varied from 30°C to 100°C. During each test condition, the temperature displayed by the system was observed and recorded. The measured temperature values were then compared with the reference test temperatures to determine the corresponding measurement error. The experimental results of the temperature sensor testing are presented in Table 2. Based on the temperature sensor test using a heater with a test range from 30°C to 100°C, the results indicate that the sensor achieved an accuracy of 99.76% with an average measurement error of 0.24%.

3.5. LDR Sensor Testing

This test was conducted to evaluate whether the light sensor module operates properly and is capable of accurately detecting variations in light intensity received by the sensor through the microcontroller. The testing procedure involved continuous acquisition of the ADC output values and the corresponding sensor resistance over a period of 24 hours under outdoor conditions. The collected data were subsequently analyzed to determine the appropriate setpoint values for implementation in the light control system, as presented in Table 3. Based on the data presented in the table, it can be observed that the sensor produces different output values corresponding to variations in light intensity at each hour over a 24-hour measurement period. These variations were used as the basis for determining the setpoint value of the control system. The threshold value applied to the LDR sensor for actuator control was defined as below 115. Accordingly, when the ambient light condition becomes dark or the measured value falls below the defined setpoint, the UV lamp actuator integrated with the LDR sensor is automatically activated, thereby ensuring adequate lighting for the system operation.

Table 3. LDR Sensor Testing Data

Time	Light Intensity Value (ADC)	Resitance Value (Ω)
07.00	211	7.28 k
08.00	372	5.72 k
09.00	502	6.31
10.00	715	2.89
11.00	736	2.61
12.00	745	2.56
13.00	403	5.73
14.00	396	5.81
15.00	420	5.72
16.00	362	5.89
17.00	119	9.37
18.00	108	9.00
19.00	90	6.91
20.00	67	10.22
21.00	48	10.31
22.00	45	10.36
23.00	12	11.31
24.00	9	11.36
01.00	1	11.47
02.00	1	11.47
03.00	1	11.47
04.00	4	11.47
05.00	11	11.24
06.00	5	11.41

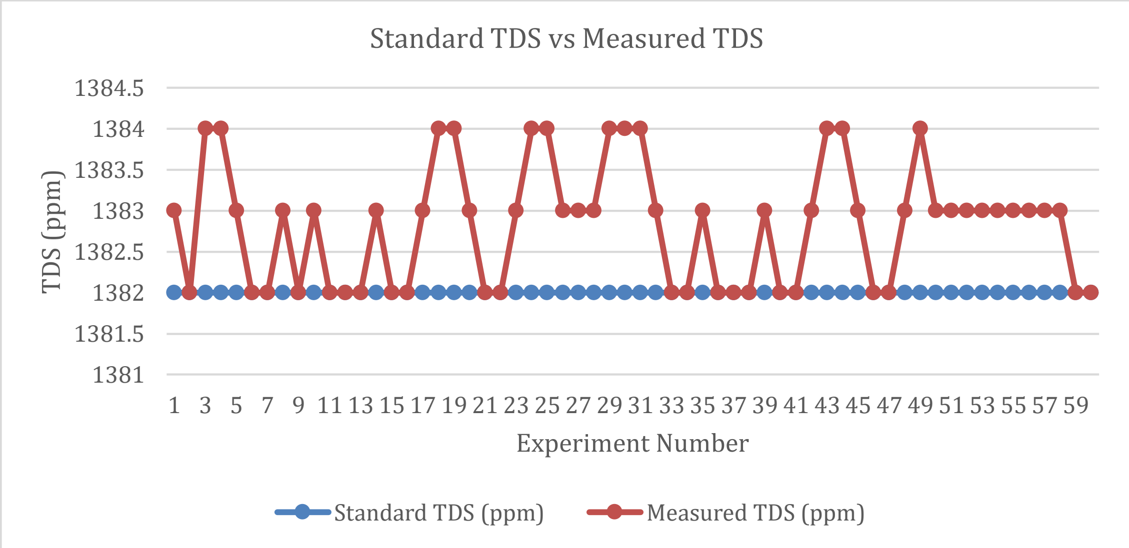

Figure 5. TDS Sensor Testing Data

3.6. Total Dissolve Solid (TDS) Sensor Testing

This test was conducted to evaluate whether the TDS sensor module operates properly and is capable of accurately measuring the total dissolved solids (TDS) in water. The testing procedure was performed using a standard TDS solution with a concentration of 1382 ppm, with a total of 60 measurement samples recorded within a duration of one minute. The collected data were used to analyze the sensor response and measurement stability under a constant TDS reference condition, as presented in Figure 5. Based on the TDS sensor test using a standard TDS solution with a concentration of 1382 ppm in Figure 5, the results indicate that the sensor achieved an accuracy of 99.94% with an average measurement error of 0.06%.

3.7. Experimental Results of Light Intensity Control

This experiment was conducted to evaluate the performance of the LDR sensor in controlling the UV grow light actuator based on ambient light intensity conditions. During the experiment based on Table 4, the LDR sensor output value was continuously observed and compared with the predefined setpoint value of 115 (ADC). When the measured LDR value dropped below the setpoint, indicating low ambient light conditions, the UV grow light was automatically activated. Conversely, when the measured value exceeded the setpoint, the UV grow light was deactivated. The results demonstrate that the LDR-based control system is capable of responding appropriately to real-time variations in light intensity, thereby ensuring adequate lighting conditions for plant growth.

Table 4. Experimental Results of LDR Sensor with UV LED Actuator

Time	LDR Setpoint (ADC)	LDR Sensor (ADC)	UV LED Activation Status
01.00	115	3	ON
02.00	115	5	ON
03.00	115	1	ON
04.00	115	1	ON
05.00	115	40	ON
06.00	115	120	OFF
07.00	115	219	OFF
08.00	115	364	OFF
09.00	115	510	OFF
10.00	115	704	OFF
11.00	115	736	OFF
12.00	115	745	OFF

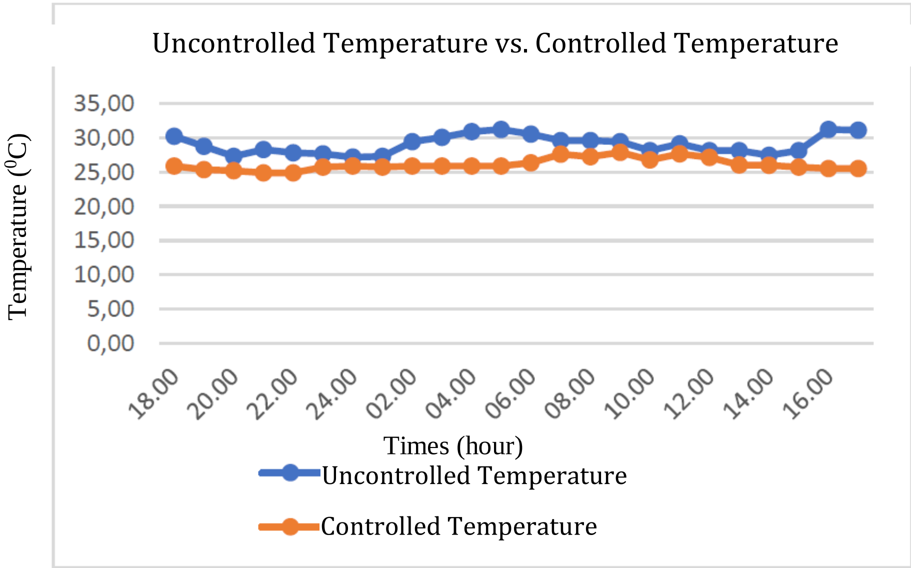

Figure 6. Comparison of Temperature Before and After Control

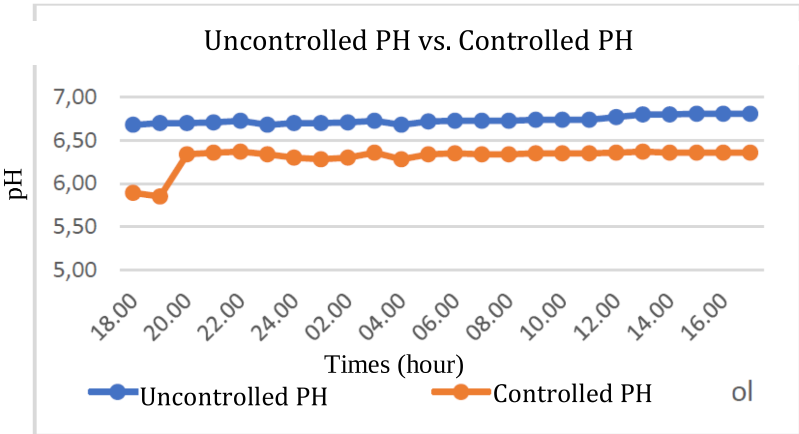

Figure 7. Comparison of PH Before and After Control

3.8. Experimental Results of Temperature Control

The graph shown in Figure 6 illustrates experimental results of temperature control. The graph Figure 6 compares uncontrolled and controlled temperatures with a set point of 28°C over a 24-hour period. The uncontrolled temperature fluctuates widely between about 27–32°C, showing noticeable instability. In contrast, the controlled temperature stays much closer to the 28°C set point, maintaining a more stable range around 25–27°C with minimal variation. This demonstrates that the control system effectively reduces temperature fluctuations and keeps the environment more consistent.

3.9. Experimental Results of PH Control

The graph shown in Figure 7 illustrates experimental results of PH control. Based on the data and the graph presented Figure 7, the pH values recorded after the control was applied, which were collected over a period of one day (24 hours), indicate that the pH level was consistently maintained within the predefined setpoint range of 5.5–6.5. As a result, the actuators were not required to operate frequently to supply acidic solution or additional water for stabilizing the pH level. The recorded pH values after control were observed to fluctuate within the range of 5.85 to 6.37. Although minor fluctuations still occurred, similar to the uncontrolled condition, all measured values remained within the acceptable setpoint limits, confirming the effectiveness of the pH control system.

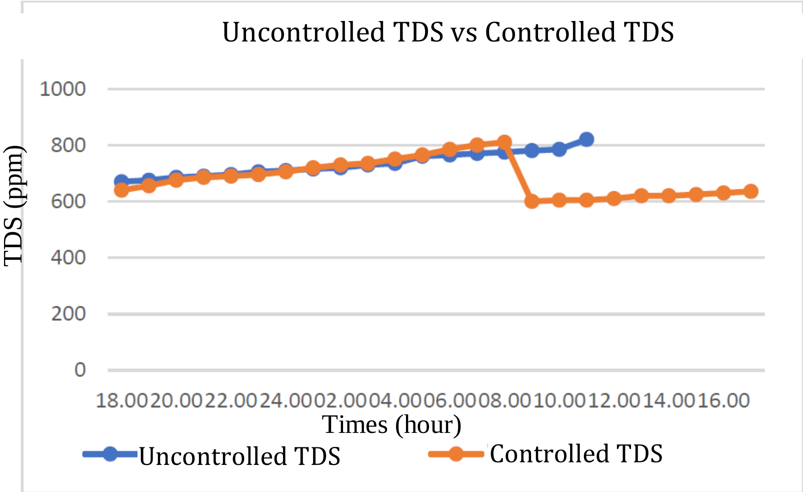

Figure 8. Comparison of TDS Before and After Control

3.10. Experimental Results of TDS Control

The graph shown in Figure 8 illustrates experimental results of TDS control. Based on the data and the graph Figure 8, the TDS values recorded after the control system was applied and observed over a 24-hour period indicate that the TDS level was successfully maintained below the designated setpoint of 840 ppm. Consequently, the actuators responsible for supplying Nutrient Solution A and Solution B did not operate frequently to stabilize the set point. Prior to control, the measured TDS values fluctuated within the range of 670–920 ppm. However, after the implementation of the control system, the TDS values were maintained within a narrower range of 640–810 ppm, which remains within the specified setpoint limits. These results demonstrate that the TDS control system effectively stabilized nutrient concentration in the hydroponic solution.

3.11. Discussions

The results of this study demonstrate that the proposed solar-powered IoT-based hydroponic system is capable of reliably monitoring and controlling key environmental parameters, including temperature, pH, TDS, and light intensity, with high sensor accuracy exceeding 99%. The implementation of closed-loop control successfully reduced parameter fluctuations and maintained all variables within predefined optimal setpoints, thereby improving environmental stability while minimizing actuator operation and energy consumption. The integration of a mobile-based IoT interface further enhanced system usability by enabling real-time monitoring and remote control, supporting practical deployment in space-limited and off-grid environments. Nevertheless, the system still exhibits several limitations. The current control strategy relies on threshold-based on–off logic, which may not optimally address nonlinear system dynamics or rapid environmental disturbances. In addition, experimental validation was conducted at the prototype scale and over a limited observation period, leaving long-term impacts on plant growth performance, yield, and nutrient use efficiency unquantified. The absence of automated sensor calibration and fault detection mechanisms may also affect long-term reliability, while dependence on Wi-Fi connectivity and solar energy availability could constrain system robustness under adverse network or weather conditions. These limitations indicate that future work should focus on adaptive or intelligent control approaches and extended agronomic evaluations to further enhance system performance and scalability.

4. Conclusion

This study has successfully designed and implemented an IoT-Based Smart Hydroponic Farming System Powered by Solar Photovoltaic Energy for Sustainable and Precision Crop Production. The system is equipped with a pH sensor, water temperature sensor, TDS sensor, and an LDR sensor for monitoring received light intensity. The experimental results indicate that the measured error rates were 0.75% for the pH sensor, 0.095% for the TDS sensor, and 0.237% for the temperature sensor, demonstrating high measurement accuracy. Furthermore, the use of an Arduino-based microcontroller operated reliably in connecting all system components to the internet via a hotspot and successfully supported real-time data transmission and reception between the smart hydroponic automation system and the Android application.

The developed smart hydroponic automation system is capable of regulating water temperature, Total Dissolved Solids (TDS), and pH levels in the hydroponic reservoir, as well as providing UV light illumination when ambient light intensity is insufficient. The system operates based on predefined setpoints, namely pH in the range of 5.5–6.5, water temperature of 28 °C, TDS setpoint of 840 ppm, and light intensity threshold of ≤115 ADC. Experimental results confirm that all sensors and actuators function properly in maintaining these parameters within the desired ranges. Furthermore, the system effectively supports the optimal growth of hydroponic lettuce plants through fully automatic operation, which can be monitored in real time via an Android application. Overall, the integrated system testing demonstrates that the proposed smart hydroponic automation system operates in accordance with the design objectives and performs reliably as planned.

References

[1] M. Dutta *et al.*, "Internet of Things-Based Smart Precision Farming in Soilless Agriculture: Opportunities and Challenges for Global Food Security," *IEEE Access*, vol. 13, pp. 34238–34268, 2025, doi: 10.1109/ACCESS.2025.3540317.

[2] W. Muhammad, L. Faridah, and S. Sutisna, "Automated Nutrient Control and Monitoring System for Internet of Things (IOT)-based Hydroponic Towers," *Jurnal Informatika dan Teknik Elektro Terapan*, vol. 13, no. 3S1, pp. 2830–7062, 2025, doi: 10.23960/JITET.V13I3S1.8101.

[3] A. B. Vernandes, M. Muqorrobin, A. Wasono, H. Santosa, and P. Rahardjo, "Desain Sistem Monitoring Daya PLTS Untuk Tanaman Hidroponik Selada Lab Listrik," *Orbith: Majalah Ilmiah Pengembangan Rekayasa dan Sosial*, vol. 21, no. 2, pp. 138–144, 2025, doi: 10.32497/ORBITH.V21I2.6771.

[4] H. Sudarso, A. Taqwa, and R. Kusumanto, "Design and Implementation of Solar Power System on Lettuce Hydroponic Greenhouse in Sekayu Musi Banyuasin Regency South Sumatera Province," *International Journal of Research in Vocational Studies (IJRVOCAS)*, vol. 3, no. 2, pp. 29–33, 2023, doi: 10.53893/IJRVOCAS.V3I2.208.

[5] A. C. H. Austria, J. S. Fabros, K. R. G. Sumilang, J. Bernardino, and A. C. Doctor, "Development of IoT Smart Greenhouse System for Hydroponic Gardens," *International Journal of Computing Sciences Research*, vol. 7, pp. 2111–2136, 2023, doi: 10.25147/ijcsr.2017.001.1.149.

[6] P. B. S. Rao *et al.*, "Automated IoT Solutions for Efficient Hydroponic Farming: Nutrients, PH and Lighting Management," *Journal Europeen des Systemes Automatises*, vol. 57, no. 5, pp. 1273–1283, Oct. 2024, doi: 10.18280/JESA.570503.

[7] T. Melkysedek, E. Hesti, and I. Salamah, "Design and Build Hydroponic Installations and Applications Using IoT-Based Multisensors with Solar Panel Electrical Energy," *IJEIS (Indonesian Journal of Electronics and Instrumentation Systems)*, vol. 13, no. 2, p. 123, 2023, doi: 10.22146/IJEIS.87906.

[8] I. I. A. Habibi, S. Wirayoga, M. Huda, and G. Y. Astono, "Modern Transformation in Agriculture for Onion Watering Automation with Solar Cell and IOT Technology," *JEECS (Journal of Electrical Engineering and Computer Sciences)*, vol. 9, no. 2, pp. 149–158, 2024, doi: 10.54732/JEECS.V9I2.7.

[9] R. Watiasih, H. Afianti, A. Arizal, and A. Ahmadi, "Solar-powered Mobile Robot for Monitoring Gas Distribution Pipe Leak Using IoT Application," *JEECS (Journal of Electrical Engineering and Computer Sciences)*, vol. 10, no. 1, pp. 86–98, 2025, doi: 10.54732/JEECS.V10I1.10.

[10] A. Sinhal, S. Choudhary, A. K. Sharma, K. Gautam, and A. Sharma, "A Novel Machine Learning Model for Dynamic Irrigation Scheduling in Water-Scarce Regions," *International Journal of Environmental Sciences*, vol. 11, no. 6, pp. 2021–2033, Aug. 2025, doi: 10.64252/13XPS114.

[11] S. Qin, S. Zhang, W. Zhong, and Z. He, "Control Algorithms for Intelligent Agriculture: Applications, Challenges, and Future Directions," *Processes 2025, Vol. 13,* vol. 13, no. 10, 2025, doi: 10.3390/PR13103061.

[12] T. Adamo, D. Caivano, L. Colizzi, G. Dimauro, and E. Guerriero, "Optimization of irrigation and fertigation in smart agriculture: An IoT-based micro-services framework," *Smart Agricultural Technology*, vol. 11, p. 100885, 2025, doi: 10.1016/J.ATECH.2025.100885.

[13] F. Dinegoro, Rusnam, and E. G. Ekaputra, "Rancang Bangun Hidroponik dengan Bantuan Pompa Bertenaga Surya," *Jurnal Teknik Pertanian Lampung*, vol. 10, no. 3, pp. 367–379, 2021, doi: 10.23960/JTEP-L.V10.I3.367-379.

[14] A. H. Santoso, M. Saputra, F. Nur, and R. Hamka, "PLTS sebagai Backup Supply pada Plant Hidroponik Nutrient Film Tehcnique (NFT) Berbasis IoT," *Elposys: Jurnal Sistem Kelistrikan*, vol. 10, no. 1, pp. 19–23, 2023, doi: 10.33795/ELPOSYS.V10I1.1009.

[15] A. H. Danarparasaji, S. I. Haryudo, T. Wrahatnolo, and M. Rohman, "IoT-Based Dual Axis Solar Tracker Design on Monocrystalline Photovoltaic for Hydroponic Plant Water Pump Power Supply,"

Journal of Telecommunication Electronics and Control Engineering (JTECE), vol. 7, no. 1, pp. 77–87, Jan. 2025, doi: 10.20895/JTECE.V7I1.1636.

[16] A. Riansyah, ; Muhammad Sagaf, and ; Munaf Ismail, "Penerapan Teknologi Smart Greenhouse Berbasis Photovoltaic dan IoT pada Budidaya Sayuran Hidroponik di Desa Pekalongan Jepara," *Abdimas Universal*, vol. 5, no. 2, pp. 284–288, 2023, doi: 10.36277/ABDIMASUNIVERSAL.V5I2.342.

[17] Y. Islamiati, T. Dewi, and Rusdianasari, "IoT Monitoring for Solar Powered Pump Applied in Hydroponic House," *International Journal of Research in Vocational Studies (IJRVOCAS)*, vol. 2, no. 2, pp. 22–30, 2022, doi: 10.53893/IJRVOCAS.V2I2.102.