2026 Volume: 02 Issue: 11 www.ijrpa.com ISSN 2456-9995 Research Article

International Journal Research Publication Analysis

Page: 01-22

DEVELOPMENT AND PRELIMINARY ASSESSMENT OF AN IOT-ENABLED VERTICAL HYDROPONIC GREENHOUSE FOR SUSTAINABLE SMALL-SCALE VEGETABLE PRODUCTION

Musa Yusufu *[1], Hassan Sabo Miya [1], Ibrahim Saidu Sintali [2], Madaki Musa Janga [3]

[1]Department of Mechatronics and D Systems Engineering, Abubakar Tafawa Balewa University Bauchi, 740272, Nigeria.

[2]Department of Mechanical and Production Engineering, Abubakar Tafawa Balewa University Bauchi, 740272, Nigeria

[3]Department of Agricultural Economics and Extension, Federal University Gashua, 631001. Nigeria.

Article Received: 02 October 2026
Article Revised: 22 October 2026
Published on: 12 November 2026

***Corresponding Author: Musa Yusufu**
Department of Mechatronics and D Systems Engineering, Abubakar Tafawa Balewa University Bauchi, 740272, Nigeria.

DOI: https://doi-doi.org/101555/ijrpa.7459

ABSTRACT

This study developed and evaluated an IoT-enabled vertical hydroponic greenhouse for small-scale urban and peri-urban vegetable production, focusing on reliability, scalability, and cost-effectiveness. Three PVC towers occupied a 2 m × 3 m greenhouse. An Arduino Mega 2560 performed local monitoring and threshold-based actuation, while an ESP32 enabled remote visualisation; nutrient circulation was scheduled and nutrient correction remained manual. During 35 days of reported operation, no system freezes or unrecoverable software crashes occurred, although the DHT11 humidity sensor exhibited moisture-related measurement anomalies. The modular three-tower design and expandable communication architecture support potential scale-up, which was not experimentally tested. Itemised prototype materials totalled ₦532,040, with no reported software licensing or hosting charges during development. In a 21-day crop comparison, hydroponic fresh biomass exceeded soil-based values for lettuce (32.43 versus 9.83 g), chilli pepper (4.60 versus 0.75 g), and spinach (32.67 versus 4.09 g). Recorded water input was 10 versus 315 L, a 96.83% reduction. The results demonstrate operational feasibility and provide a transparent capital-cost baseline, but do not establish long-term reliability, expanded-capacity performance, or financial payback.

1. INTRODUCTION

Producing vegetables reliably in the face of limited growing space, variable environmental conditions, and pressure on agricultural resources has increased interest in controlled-environment agriculture (CEA). Hydroponics offers one approach by supplying plants with a nutrient solution rather than relying on soil as the growing medium. When combined with vertical arrangements, it can also make use of otherwise under-utilized space. These features are attractive for small-scale cultivation, but they do not automatically guarantee higher productivity or lower environmental impact. The performance of a hydroponic system depends on its physical configuration, crop requirements, environmental conditions, and the way water and nutrients are managed [1], [2].

The distinction between system design and system performance is important. In a direct comparison of commercial hydroponic lettuce production with soil-based cultivation, Wang et al. [3] reported differences in yield, water productivity, crop quality, and production costs under the conditions they investigated. Their results demonstrate the potential advantages of hydroponic cultivation, but also show that outcomes must be interpreted within the specific production arrangements and management practices evaluated. At a broader environmental level, Joensuu et al. [4] compared vertical farming with greenhouse lettuce production in Finland and assessed several life-cycle impact categories. Banboukian et al. [5] similarly evaluated controlled-environment hydroponic lettuce against less intensively controlled production methods. Their analyses show why resource performance should not be judged from water input or crop output alone: energy demand, especially the use of artificial lighting, can substantially influence the overall environmental assessment.

Consistent crop growth depends on monitoring temperature, humidity, light, and nutrient-solution conditions. pH and EC indicate solution chemistry, while TDS provides an approximate measure of dissolved material but does not identify individual nutrients. Effective monitoring therefore requires appropriate sensor calibration and recognition of measurement limitations, as highlighted in reviews of greenhouse IoT and hydroponic sensing.[2], [6].

The Internet of Things (IoT) provides a way to connect sensing devices, embedded controllers, communication modules and remote interfaces within a single agricultural system. Such integration can make operating conditions easier to observe and allow programmed actions to be triggered when specified conditions occur. Song et al. [7], for example, investigated an IoT-based system for agricultural environmental monitoring, while research has also applied connected monitoring and control to vertical hydroponics. Bhat et

al.[8] evaluated an IoT-enabled vertical hydroponic system focused on nutrient management, and Hasan et al.[9] investigated automated fertigation scheduling alongside wireless microclimate monitoring in a Dutch-bucket hydroponic greenhouse. These studies illustrate the range of functions that connected systems can support. They also make it necessary to distinguish between displaying sensor readings, executing scheduled operations and changing an actuator's behaviour in response to measured conditions.

That distinction is central to the engineering problem addressed here. A remote dashboard can improve access to operating information, but remote visibility alone does not establish that the growing environment is being controlled effectively. Likewise, an automated pump schedule is not equivalent to sensor-based nutrient dosing. Sportelli et al. [1], in their review of IoT-enabled hydroponics platforms, identified fragmentation and limited interoperability among existing implementations, with many systems remaining isolated prototypes. Hosny et al. [2] likewise surveyed the communication technologies, architectures and application functions used in greenhouse IoT systems. Together, these reviews point to the importance of describing how sensing, local decisions, physical actuation and remote monitoring are integrated, rather than treating IoT connectivity itself as evidence of comprehensive automation.

This study aims to develop and assess a reliable, scalable, and cost-conscious IoT-enabled vertical hydroponic greenhouse for sustainable small-scale urban and peri-urban vegetable production. The assessment considers observed operating continuity, sensor durability, modular construction and expansion provisions, itemised prototype costs, and preliminary crop and water-input outcomes.

A 35-day operating assessment and a 21-day hydroponic-versus-soil cultivation comparison were used to evaluate prototype feasibility. The study distinguishes observed performance from projected scale-up and economic benefits, which require further testing.

2. REVIEW OF LITERATURE

2.1. Hydroponic system design, nutrient monitoring and crop response

Hydroponics encompasses several configurations, including nutrient film technique (NFT), deep-water culture (DWC), substrate-based systems and vertical towers. They differ in the way nutrient solution reaches the roots, the extent of root immersion, the role of growing media, and the management of drainage and recirculation. These construction choices influence the root-zone environment and the conditions under which crop performance should be interpreted. Chatterjee et al. [10] considered hydroponics within the broader

context of circular bioeconomy and sustainable agricultural development, and showed that the choice of growing arrangement can affect crop growth and resource use.

Yang et al. [11] compared NFT and DWC for butterhead lettuce across summer and autumn growing conditions. Their findings showed that the relative advantages of the two systems varied with season and with the outcome being assessed: NFT supported higher yield under summer conditions but was associated with more severe tip burn, whereas DWC performed better for several growth and quality measures in autumn. Chowdhury et al. [12], evaluating hydroponic systems for organic lettuce production, found that the suitability of the tested liquid organic fertilizer depended on the production arrangement, with substrate-based systems outperforming NFT on several growth measures. Taken together, these studies caution against treating hydroponics as a single, uniform cultivation method. A result obtained using one crop, nutrient formulation or hydraulic configuration cannot automatically be expected in another.

Vertical cultivation adds a spatial dimension to this problem. Planting positions at different heights can increase the use of available floor space, but the practical outcome depends on how solution is distributed, how the roots develop, and whether plants experience comparable growing conditions.

Recent IoT-based studies illustrate how hydroponic configurations can be combined with specific management interventions. Bhat et al. [8] developed and tested a vertical hydroponic system focused on nutrient management, comparing fertigation approaches and flow conditions for basil. Duangpakdee et al. [13] evaluated a deep-water-culture system for Chinese celery under different combinations of temperature and light control. The latter study reported the highest yield under combined environmental control, compared with the natural-condition treatment. These studies provide evidence that particular management interventions can be evaluated within a defined hydroponic configuration.

Nutrient-solution management is another essential part of hydroponic operation. Rusydi [14] reviewed the relationship between conductivity and TDS across different water types, supporting the need to interpret these measurements according to their measurement basis rather than as identical quantities.

The limitations of aggregate nutrient indicators become especially important when monitoring is used to guide intervention. Ahamed et al. [6] reviewed sensing technologies for precision hydroponic cultivation and explained that EC-based management does not identify or quantify individual ions. Their review also examined ion-specific sensing methods and the calibration and performance challenges associated with nutrient monitoring. Ahmed et al.

[15] reviewed contemporary smart hydroponic systems, including their enabling technologies and integration challenges. Together, these reviews indicate that connected sensing can improve access to nutrient-solution information, but the quality and specificity of that information remain important constraints on the decisions that can be made from it.

Individual system studies demonstrate different ways of addressing these needs. Awal et al. [16] developed a small-scale IoT-based hydroponic system for spinach that monitored pH, temperature, TDS and EC and incorporated control functions. Jain and Kaur [17] presented an IoT-based NFT system designed to monitor and automatically adjust EC and pH through nutrient and pH-solution delivery. These implementations illustrate the distinction between collecting nutrient-solution readings and using them to trigger corrective dosing. They also show why an account of a hydroponic system should specify which variables are measured, which actions are automatic, and which adjustments still require a human operator.

2.2. IoT architecture, environmental control and remote monitoring

IoT-enabled greenhouses combine sensing, embedded processing, communication, and user interfaces to support monitoring, scheduled operation, or condition-based control. These functions are distinct and require separate performance evidence. For example, Duangpakdee et al. [13] evaluated temperature and light-control treatments in hydroponic Chinese celery, linking environmental interventions to crop outcomes. Therefore, demonstrating effective control requires documenting the measured conditions, control rules, resulting actuator responses, and associated outcomes.

More advanced approaches to control and decision support have also been explored. Rathor et al. [18] reviewed IoT- and AI-driven technologies for vertical farming, including applications in environmental monitoring, crop diagnosis and data-driven management. Hasan et al. [19] investigated the use of IoT and deep learning in tomato cultivation and pest management. These studies indicate that data-driven methods can extend the functions of connected agricultural systems, but their use should not be conflated with straightforward threshold logic. Machine learning, prediction and closed-loop nutrient regulation require their own methods and validation.

The communication and interface layer also influences how useful the system is to its operator. Austria et al. [20] developed an IoT smart greenhouse system for hydroponic gardens, integrating a physical system with remote monitoring and a mobile application. Seetaram et al.[21] reported an ESP32-based greenhouse monitoring and control implementation, while Saravanan et al. [22] described a smart hydroponic system incorporating an Arduino controller, wireless communication, cloud data and a web

dashboard. These studies show that accessible microcontrollers and web or mobile interfaces can be used in agricultural monitoring architectures. However, their reported functions and validation measures differ, so their performance cannot be compared solely on the basis of connectivity.

Rofiansyah et al. [23] extended hydroponic monitoring through image processing and a mobile interface in the HydroFarm system. Their evaluation included image-classification performance and usability measures. These metrics address different questions: classification accuracy concerns the evaluated image-analysis task, while a usability score concerns interaction with the interface. Neither, on its own, establishes nutrient-control accuracy or improved crop yield. This is an important consideration when interpreting increasingly feature-rich IoT systems, since a larger number of software functions does not necessarily imply stronger agronomic evidence.

Reviews of the broader field reinforce the need for careful system description. Ahmed et al. [15] identified middleware, interoperability and communication as relevant concerns in contemporary smart hydroponics, while Malabadi et al. [24] reviewed vertical hydroponic farming and IoT technologies alongside environmental and deployment considerations. Dsouza et al. [25], through a systematic scoping review of controlled-environment agriculture research, documented the breadth of topics and approaches represented in the field. The review by Sportelli et al. [1] is particularly relevant to implementation maturity: its analysis of 74 studies found that many IoT-enabled hydroponic platforms remain custom-built, with limited standardization and relatively few demonstrations of readiness for wider deployment. The implication for prototype research is that architecture, implemented functions and validation should be reported transparently rather than inferred from the presence of IoT connectivity.

2.3. Multi-crop performance, resource assessment and research gap

Crop performance is shaped by more than the presence of sensors or a connected controller. Species differ in growth rate, nutrient demand, root development, crop duration and the appropriate harvest endpoint. The findings from lettuce and basil studies therefore provide useful comparisons of particular growing arrangements, but they cannot be transferred directly to chilli pepper or spinach. Yang et al. [11] demonstrated that lettuce response to NFT and DWC differed with season and outcome, while Chowdhury et al. [12] showed that lettuce growth under organic nutrient management varied across hydroponic configurations. These findings reinforce the need to identify the crop, growing conditions and measured endpoint when interpreting a comparative trial.

Nutrient management can also influence plant growth independently of the monitoring technology. Moreno-Aguilera et al. [26] evaluated lettuce grown with different concentrations of Steiner nutrient solution in an IoT-monitored cultivation experiment. Their work provides an example of using crop measurements to examine a defined nutrient treatment. Zhou et al. [27] investigated beneficial bacterial endophytes and spinach growth under indoor vertical hydroponics, while Dasgan et al. [28] examined biofertilizers and leaf quality in hydroponically grown baby spinach. Keskin et al. [29] investigated fulvic acid, amino acids and vermicompost as interventions affecting yield and nutrient profile in soilless iceberg lettuce. These studies focus on specific biological or nutrient-management factors, rather than on IoT integration alone. Their relevance is that observed crop outcomes may reflect several interacting aspects of cultivation, which must be distinguished when drawing conclusions from a system comparison.

Water input is another important measure, but it must be defined carefully. The total volume added to a growing system is not necessarily equivalent to the volume consumed by plants, because water may remain in a reservoir or growing medium, be discharged, or be lost through evaporation and transpiration. Wang et al.[3] compared hydroponic and soil-based lettuce production and reported differences in water productivity under the specific conditions they studied. Yang et al. [11] found that water consumption and water-use efficiency also differed between NFT and DWC and varied with growing season. These findings make the measurement boundary essential when reporting water-related results.

Other studies illustrate why water should be considered alongside the broader production system. Li et al. [30] investigated an IoT-based variable irrigation approach in a solar greenhouse and assessed its application to lettuce. Hasan et al.[9] evaluated sensor-informed fertigation in a Dutch-bucket hydroponic cucumber system and reported higher water productivity alongside crop-performance differences compared with soil cultivation. Although these studies are relevant to the concept resource management, their irrigation strategies, crop species, and system boundaries differ from the present prototype.

Environmental assessments add a further dimension. Joensuu et al. [4] compared vertical-farming and greenhouse lettuce production in Finland using life-cycle assessment, while Banboukian et al. [5] examined the environmental impacts of lettuce production across open-field, greenhouse and controlled-environment hydroponic methods. Both studies show that resource outcomes depend on the production boundary and the inputs included in the analysis. Wang et al. [3] discussed pathways toward sustainable, resilient and scalable indoor agriculture, placing individual production technologies within a wider systems context.

Chatterjee et al. [10] likewise considered hydroponics in relation to circular bioeconomy and resource recovery. These perspectives support a cautious interpretation of resource-saving claims: lower recorded water input may be a useful observation, but it is not sufficient by itself to establish overall sustainability.

Existing studies emphasize hydroponic design, IoT sensing and control, and transparent performance evaluation [1], [2], [6], [15], [18]. For small-scale urban and peri-urban applications, reliability, expansion potential, and upfront affordability must also be assessed alongside crop and resource outcomes. This study contributes a three-tower IoT greenhouse with reported operating observations, an itemised capital-cost baseline, and preliminary multi-crop biomass and water-input comparisons; longer-term reliability, larger installations, and financial returns remain outside its experimental scope.

3. MATERIALS AND METHODS

The engineering design targeted a compact, accessible, and potentially expandable IoT-enabled hydroponic greenhouse for small-scale urban and peri-urban vegetable production. Three food-grade PVC towers were installed in a greenhouse measuring approximately 2 m × 3 m × 2 m. The system separated cultivation and sensing, local embedded control and wireless communication, and remote monitoring into functional layers. An Arduino Mega 2560 executed threshold-based actuation and scheduled circulation, while an ESP32 supported remote visualisation. This separation allows programmed local functions to operate independently of dashboard presentation, although failure recovery and uptime were not tested quantitatively. Nutrient adjustments remained manual. Following a 14-day nursery phase, lettuce, chilli pepper, and spinach were assessed in a 21-day hydroponic versus soil-based trial.

The engineering assessment drew on a reported 35-day operating observation, including controller continuity and sensor behaviour, and on the prototype bill of materials. Scalability was evaluated from the installed three-tower layout and documented hardware/software expansion provisions; no additional-tower stress test was performed. Cost analysis summed approximate component expenditures in Nigerian naira and distinguished initial materials from unmeasured recurring costs. The cultivation comparison covered the 21-day active growing period within the wider operating assessment.

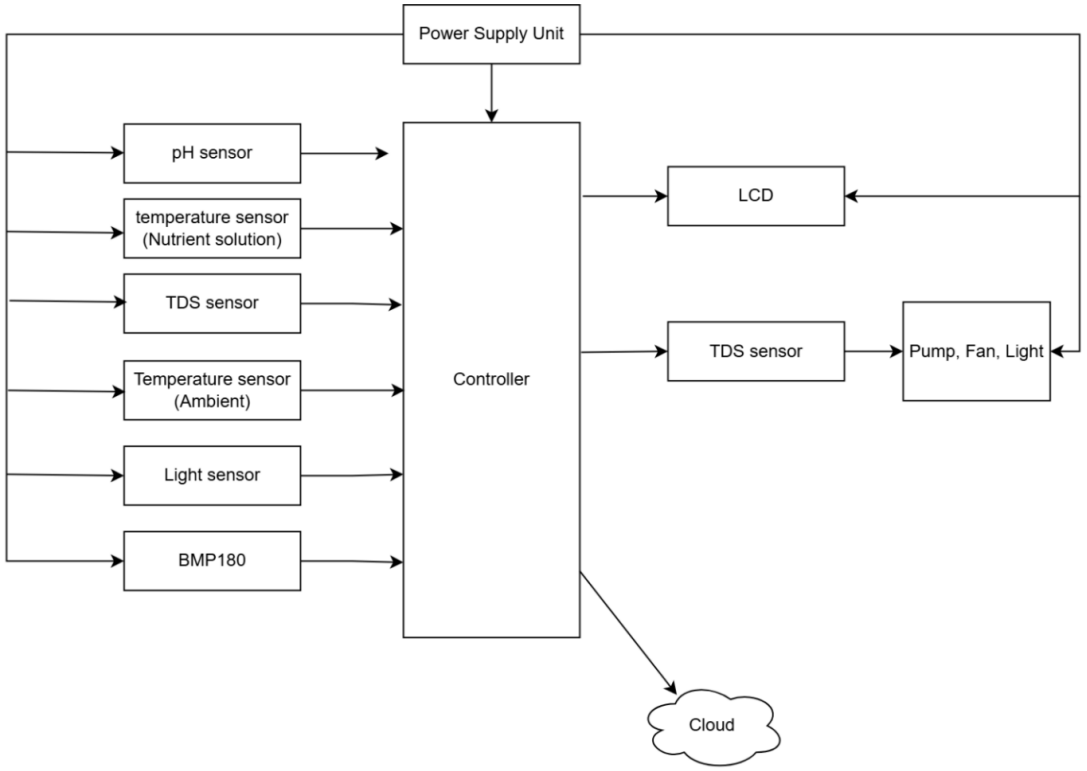

Figure 1: Functional architecture of the IoT-monitored vertical hydroponic greenhouse.

Table 1. Principal materials and their functions in the developed system.

Material or component	Function and justification
Wooden greenhouse frame and UV-stabilized nylon covering	Provided the physical enclosure for the cultivation setup while allowing a dedicated space for monitoring and environmental actuation.
Three food-grade PVC vertical towers	Supported the vertical arrangement of plants and increased the number of growing positions within the available floor area.
Net pots and porous supporting medium	Held the seedlings in position while allowing their roots to access the nutrient solution.
Nutrient-solution reservoir, circulation pump, and irrigation tubing	Stored and delivered the nutrient solution through the hydroponic arrangement.
Arduino Mega 2560	Executed local sensor acquisition and predefined control logic; its available input/output connections supported integration of multiple sensors and relay-controlled devices.
ESP32 development board	Provided Wi-Fi connectivity and served as the communication gateway between the local controller and the remote monitoring infrastructure.
pH and TDS sensing modules	Supported monitoring of nutrient-solution acidity and an indirect indication of dissolved ionic concentration.
DS18B20 waterproof temperature probes	Provided measurements of nutrient-solution temperature, where installed in the experimental configuration.
DHT-type temperature and relative-humidity sensors	Monitored the greenhouse atmosphere to support environmental observation and threshold-based actuation.
Light-dependent resistors (LDRs)	Provided relative measurements of light intensity at selected locations within the greenhouse.
Relay module and environmental actuators	Allowed the controller to switch selected devices, including fans and other installed environmental-control equipment.
Local display and keypad	Supported local observation of system status and direct user interaction.
Embedded firmware and remote dashboard	Enabled local decision logic, wireless transmission, and remote presentation of selected sensor readings and system states.

The firmware for the Arduino Mega 2560 and ESP32 was developed using the Arduino integrated development environment, with C++ used for embedded programming. The Arduino firmware initialized the connected sensors, acquired measurements, and executed conditional logic for local actuation. The ESP32 firmware managed Wi-Fi connectivity and the transmission of selected measurements to the remote monitoring infrastructure.

The operational sequence as shown in figure 3 consisted of sensor acquisition, local evaluation of the monitored conditions, actuation where a programmed threshold was met, and transmission of measurements for remote visualization. This sequence was repeated during operation to provide continuing environmental observation and scheduled system activity.

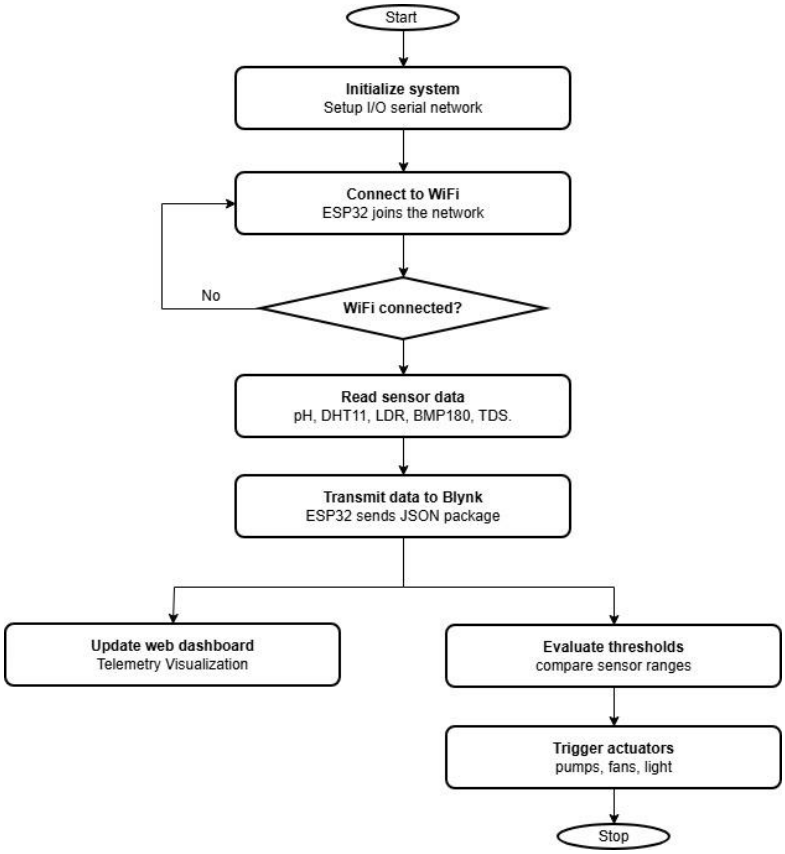

Figure 3: System flowchart illustrating the Data and control logic.

Environmental control used predefined rules, with fans activated when the temperature exceeded 28 °C. The nutrient-solution pump operated on a fixed schedule of 5–10 min on and 30–35 min off. These functions provided simple, rule-based environmental actuation and scheduled circulation rather than predictive or adaptive control. The system monitored pH and TDS, with EC-related readings manually verified using a handheld meter; nutrient mixing and solution adjustment remained manual. An ESP32 gateway transmitted selected

sensor readings to a custom Vercel-hosted dashboard, which displayed measurements and system status through numerical indicators, gauges, and graphs for remote monitoring.

The cultivation experiment comprised a 14-day nursery phase followed by a 21-day comparative growing period involving lettuce, chilli pepper, and spinach, with soil-based cultivation serving as the comparison treatment. Seedlings were established in a soil–coco-coir medium before transplantation. Those assigned to hydroponics had their roots gently washed to remove adhering soil before placement in net pots within the vertical PVC towers, while comparison plants were transferred to pots containing the documented growing medium.



Figure 4: Transplantation of the seedlings into the vertical hydroponic towers.

Data collection covered environmental and nutrient-solution monitoring, fresh biomass, and water input. Air temperature, relative humidity, light intensity, and nutrient-solution indicators were recorded through the connected sensors, with EC/TDS readings manually cross-checked using a handheld meter. Fresh biomass of lettuce, chilli pepper, and spinach under hydroponic and soil-based treatments was measured using an electronic balance (Figure 8). The percentage biomass increase was calculated as:

$$Change\ (\%) = \frac{\bar{X}_H}{\bar{X}_s} \times 100\%$$

where $\bar{X}_H$ *represents the reported mean fresh biomass for the hydroponic treatment and* $\bar{X}_s$ represents the reported mean fresh biomass for the soil-based treatment.

Total water input recorded over the 21-day comparative period was compared using

$$Reduction\ (\%) = \frac{V_s - V_H}{V_s} \times 100\%$$

where V_s is the water volume for the soil-based treatment and V_H is the reported volume for the hydroponic treatment.

Fresh biomass was compared separately for each crop using independent-samples t-tests at a significance level of (α=0.05), with three replicates per treatment. For the equal-variance test, the statistic was calculated as

$$t = \frac{\bar{X}_H - \bar{X}_s}{S_p\sqrt{\frac{1}{n_H} - \frac{1}{n_s}}}$$

Where the pooled variance is:

$$S_p = \frac{(n_H - 1){S_H}^2 - (n_s - 1){S_s}^2}{n_H + n_s - 2}$$

Here, ${S_H}^2$and ${S_S}^2$ denote the sample variances, while n_H and n_s are the respective sample sizes. The reported test statistics could not be independently reproduced because the raw plant-level measurements and complete test output were unavailable.

4. RESULTS AND DISCUSSION

The prototype integrated sensor acquisition, local control, wireless communication, and remote visualization. The Arduino Mega 2560 executed predefined control functions, while the ESP32 transmitted selected readings to a web dashboard for monitoring environmental conditions and system states (Figure 5).

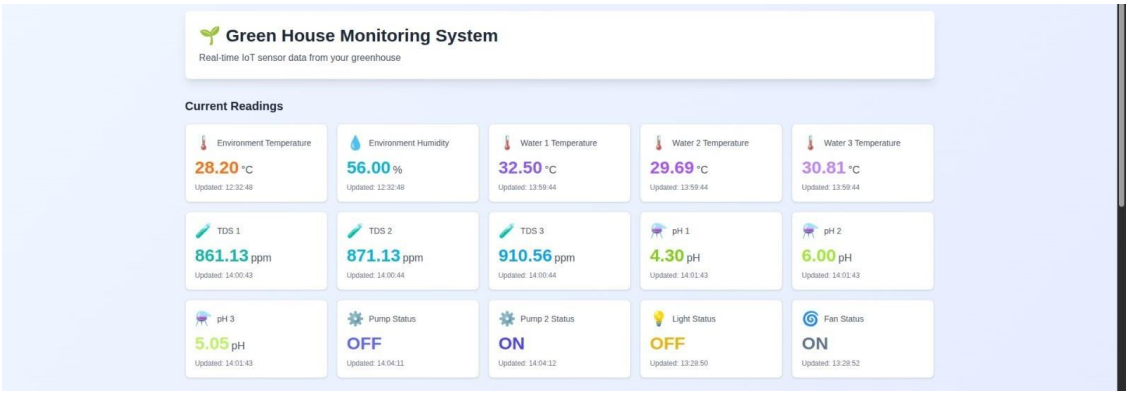

Figure 5. Main dashboard interface displaying sensor telemetry.

The prototype demonstrated integrated monitoring, actuation, and remote visualization. However, sensor accuracy, communication latency, data loss, network uptime, and actuator response time were not quantitatively validated.

Environmental Monitoring and Threshold-Based Control

The system monitored greenhouse air temperature, relative humidity, light intensity, and nutrient-solution temperature during operation. The programmed environmental response used a temperature threshold above 28 °C to trigger selected ventilation equipment. Nutrient-solution circulation operated according to a predefined schedule rather than a continuously optimized control policy.

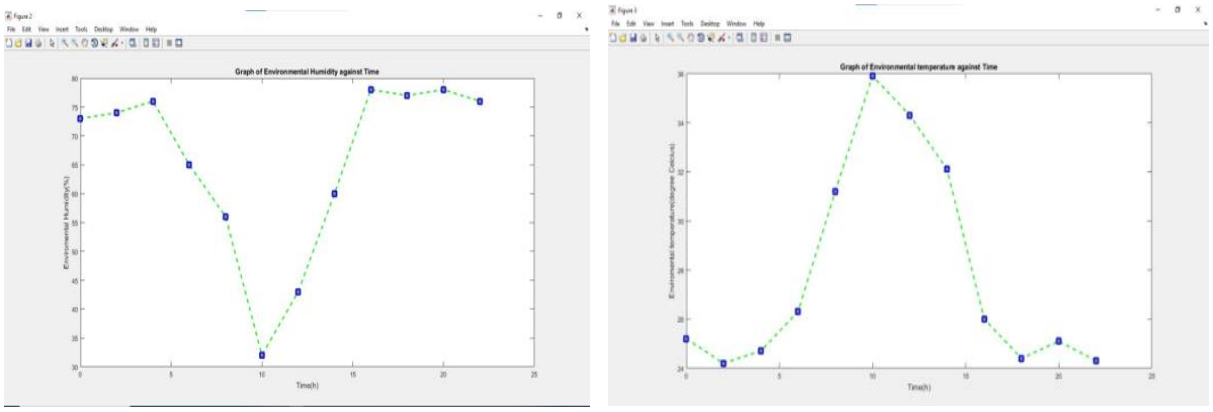

Figure 6. Twenty-four-hour greenhouse microclimate profiles showing (a) ambient temperature and (b) relative humidity.

The recorded profile showed diurnal variation in greenhouse temperature, with a reported peak of 35.9 °C. Relative humidity also varied during the observation period. These profiles describe the environmental conditions encountered during the trial and provide context for interpreting crop growth; they do not establish that the greenhouse remained within an optimal range throughout the day.



Figure 7. Greenhouse temperature variation under conditions with and without automated temperature control.

Nutrient-Solution Monitoring and Verification

Nutrient-solution monitoring covered EC, TDS, pH, and solution temperature where measurements were available. The recorded profiles were examined separately for lettuce, chilli pepper, and spinach to describe the solution conditions observed during the trial.

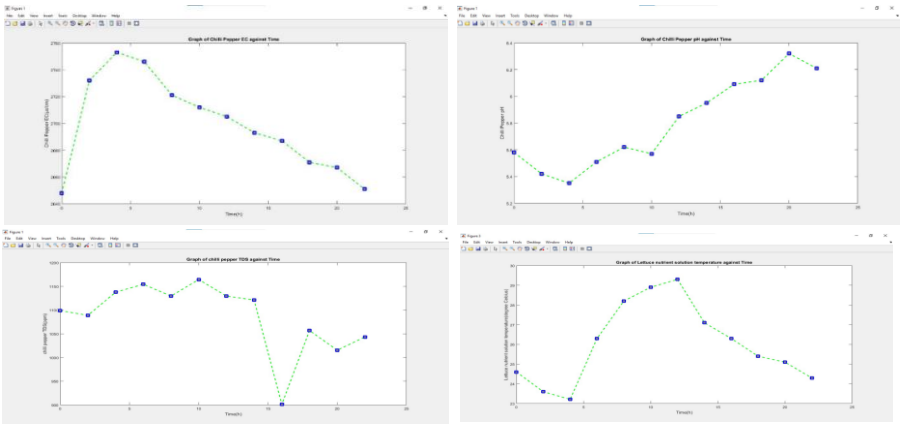

Figure 8. Twenty-four-hour nutrient-solution profiles for chilli pepper showing (a) electrical conductivity, (b) pH, (c) total dissolved solids, and (d) solution temperature.

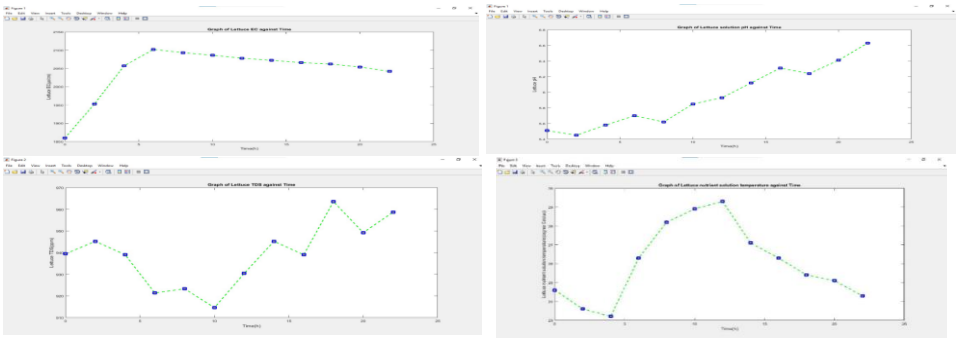

Figure 9. Twenty-four-hour nutrient-solution profiles for lettuce showing (a) electrical conductivity, (b) pH, (c) total dissolved solids, and (d) solution temperature.

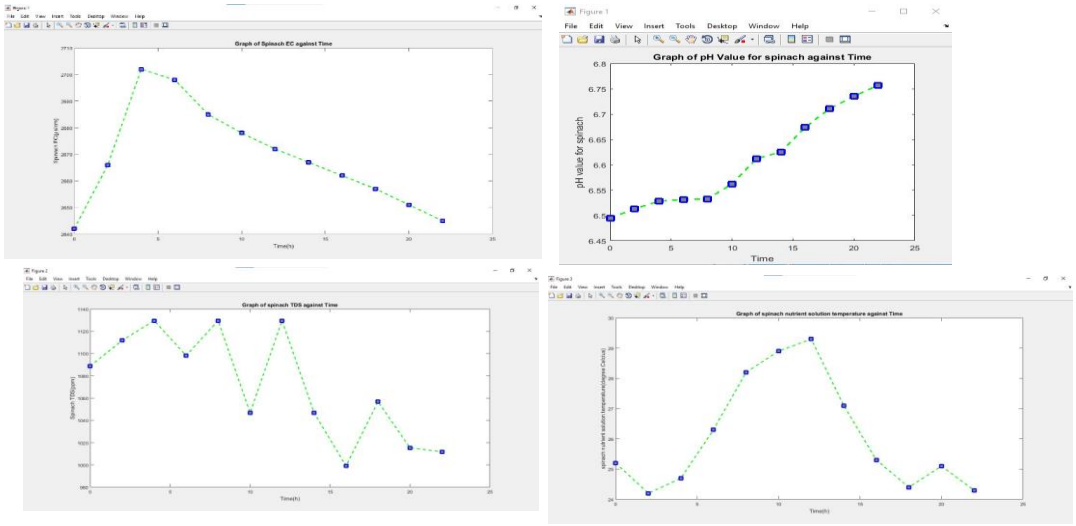

Figure 10. Twenty-four-hour nutrient-solution profiles for spinach showing (a) electrical conductivity, (b) pH, (c) total dissolved solids, and (d) solution temperature.

Recorded EC values were approximately 2810 µS/cm for chilli pepper, 1828 µS/cm for spinach, and 1100 µS/cm for lettuce, while pH ranged from 5.45–6.63 for lettuce and 6.49–6.76 for spinach. Selected EC and TDS readings were manually cross-checked using a handheld digital meter, while nutrient-solution adjustments remained manual. These measurements describe the conditions observed during the trial and establishing effort toward measuring crop-specific optima or improving sensor accuracy.

Comparative Crop Biomass

The comparative cultivation trial evaluated lettuce (*Lactuca sativa*), chilli pepper (*Capsicum annuum*), and spinach (*Spinacia oleracea*) under hydroponic and soil-based cultivation. The reported comparative growing period was 21 days following the nursery stage. Final fresh biomass was used to compare plant growth between the two cultivation treatments.

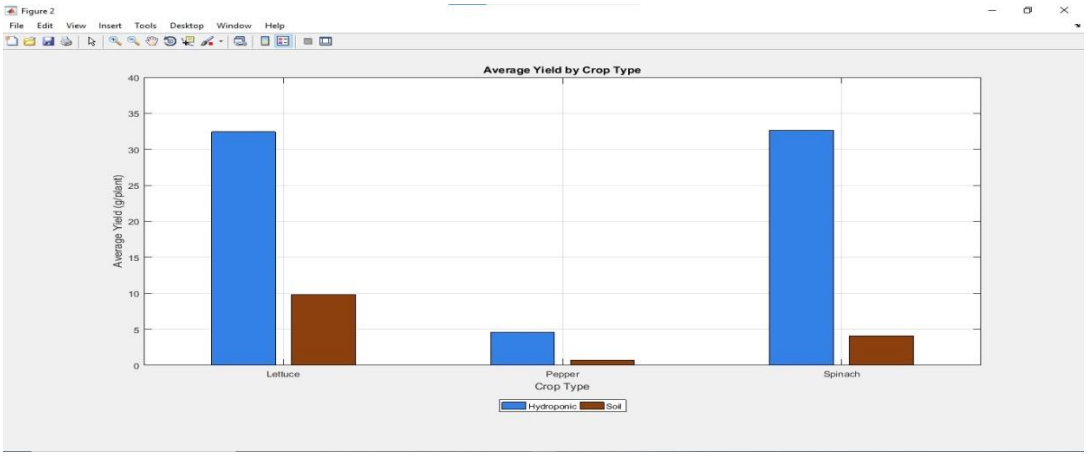

Figure 18. Comparison of mean final fresh biomass between hydroponic and soil-based cultivation for lettuce, chilli pepper, and spinach.

The hydroponic treatment produced higher reported mean fresh biomass than the soil-based treatment for all three crops. The mean values and percentage differences are presented in Table 3.

Table 2. Reported final fresh biomass under hydroponic and soil-based cultivation.

Crop	Hydroponic biomass (g)	Soil-based biomass (g)	Reported increase (%)	Calculated t-statistic
Lettuce	32.43	9.83	229.91	5.72
Chilli pepper	4.60	0.75	513.33	5.18
Spinach	32.67	4.09	698.78	6.04

Hydroponically grown lettuce recorded a mean fresh biomass of 32.43 g, compared with 9.83 g under soil-based cultivation, representing a 229.91% increase. This indicates greater biomass accumulation under the tested hydroponic configuration, although the difference cannot be attributed solely to IoT monitoring or threshold-based control.

Chilli pepper recorded a mean fresh biomass of 4.60 g under hydroponic cultivation and 0.75 g under soil-based cultivation, representing a 513.33% increase. Early flower-bud development was observed in the hydroponic plants; however, these measurements reflect early-stage growth rather than mature fruit yield.

Spinach recorded a mean fresh biomass of 32.67 g under hydroponic cultivation, compared with 4.09 g under soil-based cultivation, representing a 698.78% increase, the largest percentage difference among the three crops. This indicates greater fresh biomass under the tested hydroponic conditions, although multiple differences between the cultivation systems may have contributed to the outcome.

The reported independent-samples t-statistics were 5.72 for lettuce, 5.18 for chilli pepper, and 6.04 for spinach, with all comparisons reported as ($p<0.01$). However, the absence of raw plant-level data and dispersion statistics prevents independent verification, while the small sample size and potential dependence between plants sharing growing infrastructure limit the strength and generalizability of the findings.

Over the 21-day comparison, recorded water input was 10 L for hydroponic cultivation and 315 L for soil-based cultivation, equivalent to a 96.83% reduction in water input for the hydroponic system. This difference is consistent with the potential for recirculating hydroponic arrangements to reuse nutrient solution rather than applying water directly to a soil-based growing medium.

Engineering Assessment: Reliability, Scalability, and Cost

Operational reliability

The complete prototype was reportedly operated for 35 days without a system freeze or unrecoverable software crash. The Arduino Mega 2560 executed local control while the ESP32 supported remote data transmission, separating local actions from dashboard presentation. Electronics were housed in a protective enclosure. DS18B20 temperature probes and TDS modules remained operational in the reported observation, whereas the DHT11 humidity sensor occasionally produced anomalously low readings associated with moisture exposure. Thus, the trial supports short-term controller continuity but also identifies a sensor-durability weakness; uptime percentages, packet loss, and recovery after faults were not measured.

Modular scalability

The three PVC towers occupied a greenhouse footprint of approximately 2 m × 3 m (6 m²), demonstrating compact multi-tower integration. The use of repeatable tower modules and provision for additional ESP32 reporting nodes offers a plausible route to physical and digital expansion. However, a proposed increase to ten or more towers was not experimentally validated; available pump head, flow distribution, power demand, and communication capacity must be tested before specifying a supported maximum installation size.

Prototype cost assessment

The itemised bill of materials totalled approximately ₦532,040. The pH and TDS sensing modules accounted for ₦210,540 (39.6%) of this total, while the mechanical construction package and hose accounted for ₦142,500 (26.8%). Arduino and ESP32 boards together cost ₦36,500 (6.9%). The use of locally fabricated PVC structures and open-development microcontrollers avoided proprietary controller procurement, and the reported Vercel/Blynk development configuration incurred no additional software licensing or hosting charges. This is a prototype capital-material estimate, not a full installed or lifecycle cost: labour, electricity, internet, maintenance, replacement sensors, and future service-tier charges were not quantified.

Table 3. Itemised approximate prototype material costs. (₦).

Category	Component	Qty	Unit (₦)	Total (₦)
Processing	Arduino Mega 2560	1	25,000	25,000
Processing	ESP32 Dev Kit	1	11,500	11,500
Processing	IC base	2	500	1,000
Sensing	pH sensor module (E-201C)	3	49,000	147,000
Sensing	TDS sensor module	3	21,180	63,540
Sensing	DHT11 temperature/humidity sensor	2	3,000	6,000
Sensing	LDR	3	1,000	3,000
Sensing	4×4 keypad	1	2,000	2,000
Actuation	8-channel relay module	1	15,000	15,000
Actuation	12 V DC pump	3	13,000	39,000
Actuation	Voltage regulator	3	500	1,500
Output	20×4 LCD with I²C adapter	1	9,500	9,500
Power	12 V power supply	1	6,500	6,500
Power	LM2596 buck converter	1	3,500	3,500
Support	Vero board, wiring, resistors	1	1,000	1,000
Support	Project enclosure	1	4,500	4,500
Mechanical	PVC, net pots, frame and covering (lot)	1	140,000	140,000
Mechanical	Hose (roll)	1	2,500	2,500
Consumables	Fertilizer and coconut husk (lot)	1	50,000	50,000
TOTAL				532,040

The three pH modules alone represented ₦147,000 (27.6% of materials). Reducing sensor count could lower expenditure in a simplified household version, but such savings would need to be balanced against monitoring coverage and validated experimentally. No commercial-price comparison, payback calculation, or profitability estimate was available; therefore, economic cost-effectiveness is discussed as a design potential rather than a demonstrated return on investment.

DISCUSSION OF RESULTS

The prototype integrated Arduino-based local control, ESP32 communication, threshold-based actuation, scheduled circulation, and remote monitoring. During the 21-day crop comparison, mean hydroponic fresh biomass exceeded soil-based values for lettuce (32.43 versus 9.83 g), chilli pepper (4.60 versus 0.75 g), and spinach (32.67 versus 4.09 g). Recorded water input was 10 L for hydroponics and 315 L for soil cultivation, representing a 96.83% reduction in water additions. These outcomes reflect the complete cultivation systems rather than the isolated effect of IoT functions.

The additional engineering assessment strengthens the suitability argument. The reported 35-day period without a system freeze or unrecoverable crash provides evidence of short-term controller continuity, although moisture-related DHT11 anomalies reveal an instrumentation

limitation. Three modular towers within a 6 m² footprint and an architecture allowing additional ESP32 nodes support design-level scalability, but hydraulic and network capacity at larger scale remain unverified. The ₦532,040 itemised material cost provides a reproducible affordability baseline, while free-tier software services avoided reported licensing and hosting charges during the prototype period. These findings support preliminary technical and economic feasibility, not a proven payback period or superiority over commercial alternatives. The short crop trial, limited replication, incomplete water balance, and unmeasured electricity and maintenance costs further constrain sustainability and lifetime-cost conclusions.

5. CONCLUSION

The developed IoT-enabled vertical hydroponic greenhouse demonstrated short-term operational continuity, modular multi-tower integration, and a documented prototype material cost of ₦532,040. Across 35 days of reported operation, no system freezes or unrecoverable software crash occurred, although the DHT11 humidity sensor showed moisture-related anomalies. Three PVC towers fitted within a 6 m² greenhouse, providing a compact design with potential for modular expansion. During the 21-day cultivation comparison, hydroponic lettuce, chilli pepper, and spinach recorded higher mean fresh biomass than soil-based controls (32.43 versus 9.83 g; 4.60 versus 0.75 g; and 32.67 versus 4.09 g), while recorded water additions were 96.83% lower (10 versus 315 L). Together, these results support prototype-level reliability, design scalability, and initial capital-cost transparency relevant to small-scale urban and peri-urban cultivation. Long-term reliability, expanded-system capacity, and lifecycle cost-effectiveness require further verification.

5.1. Recommendations for Further Development

Future work should measure controller uptime, recovery from communication and power interruptions, sensor drift, and actuator response under longer operating periods, replacing moisture-sensitive DHT11 sensors with appropriately protected probes. Expansion trials should quantify pump flow, pressure distribution, nutrient uniformity, electrical load, and network capacity as towers are added. A full economic assessment should include electricity, maintenance, replacements, labour, crop revenue, and sensitivity to changes in free-tier cloud services. Longer crop trials, independent replication, mature chilli yield, and a complete water balance are also needed to establish sustained productivity and resource efficiency.

REFERENCES

1. M. Sportelli, D. La Rosa, A. Crivello, D. Pineda-Medina, M. Bacco, and P. Barsocchi, "Beyond Prototypes: What Is Missing to Fill the Gaps in IoT-Enabled Hydroponics Platforms," *Horticulturae*, vol. 11, no. 11, p. 1322, Nov. 2025, doi: 10.3390/horticulturae11111322.
2. K. M. Hosny, W. M. El-Hady, and F. M. Samy, "Technologies, Protocols, and applications of Internet of Things in greenhouse Farming: A survey of recent advances," *Inf. Process. Agric.*, vol. 12, no. 1, pp. 91–111, Mar. 2025, doi: 10.1016/j.inpa.2024.04.002.
3. L. Wang *et al.*, "Performance analysis of two typical greenhouse lettuce production systems: commercial hydroponic production and traditional soil cultivation," *Front. Plant Sci.*, vol. 14, Jul. 2023, doi: 10.3389/fpls.2023.1165856.
4. K. Joensuu, T. Kotilainen, K. Räsänen, M. Rantanen, K. Usva, and F. Silvenius, "Assessment of climate change impact and resource-use efficiency of lettuce production in vertical farming and greenhouse production in Finland: a case study," *Int. J. Life Cycle Assess.*, vol. 29, no. 10, pp. 1932–1944, Oct. 2024, doi: 10.1007/s11367-024-02343-5.
5. A. Banboukian, Y. Chen, and V. M. Thomas, "The challenges of controlled environment hydroponic farming: a life cycle assessment of lettuce," *Int. J. Life Cycle Assess.*, vol. 30, no. 7, pp. 1691–1704, Jul. 2025, doi: 10.1007/s11367-025-02463-6.
6. M. S. Ahamed *et al.*, "A comprehensive review of advances in sensing and monitoring technologies for precision hydroponic cultivation," *Comput. Electron. Agric.*, vol. 237, p. 110601, Oct. 2025, doi: 10.1016/j.compag.2025.110601.
7. Y. Song, J. Bi, and X. Wang, "Design and implementation of intelligent monitoring system for agricultural environment in IoT," *Internet Things*, vol. 25, p. 101029, Apr. 2024, doi: 10.1016/j.iot.2023.101029.
8. A. G. Bhat, M. Hasan, D. K. Singh, R. N. Sahoo, M. Yeasin, and V. K. S, "Design, Development and Testing of an IoT-Based Smart Vertical Hydroponic System for Optimized Nutrient Management in a Controlled Environment," *Irrig. Drain.*, vol. 74, no. 5, pp. 1904–1920, Dec. 2025, doi: 10.1002/ird.4002.
9. M. Hasan *et al.*, "IoT-Based Smart Fertigation Scheduling and Wireless Microclimate Monitoring for a Greenhouse Dutch Bucket Hydroponic System," *Irrig. Drain.*, vol. 74, no. 5, pp. 1889–1903, Dec. 2025, doi: 10.1002/ird.70012.
10. A. Chatterjee *et al.*, "Demystifying the integration of hydroponics cultivation system reinforcing bioeconomy and sustainable agricultural growth," *Sci. Hortic.*, vol. 341, p. 113973, Feb. 2025, doi: 10.1016/j.scienta.2025.113973.

11. T. Yang, U. Samarakoon, and J. Altland, “Growth, phytochemical concentration, nutrient uptake, and water consumption of butterhead lettuce in response to hydroponic system design and growing season,” *Sci. Hortic.*, vol. 332, p. 113201, Jun. 2024, doi: 10.1016/j.scienta.2024.113201.
12. M. Chowdhury, U. C. Samarakoon, and J. E. Altland, “Evaluation of hydroponic systems for organic lettuce production in controlled environment,” *Front. Plant Sci.*, vol. 15, Aug. 2024, doi: 10.3389/fpls.2024.1401089.
13. K. Duangpakdee, G. Thananta, and S. Sukpancharoen, “IoT enhanced deep water culture hydroponic system for optimizing Chinese celery yield and economic evaluation,” *Smart Agric. Technol.*, vol. 9, p. 100545, Dec. 2024, doi: 10.1016/j.atech.2024.100545.
14. A. F. Rusydi, “Correlation between conductivity and total dissolved solid in various type of water: A review,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 118, p. 012019, Feb. 2018, doi: 10.1088/1755-1315/118/1/012019.
15. A. Ahmed, R. Alnawasrah, B. Almadani, F. Aliyu, and M. Ghaleb, “Contemporary smart hydroponics systems: Taxonomy, enabling technologies, and challenges,” *Internet Things*, vol. 34, p. 101794, Nov. 2025, doi: 10.1016/j.iot.2025.101794.
16. Md. A. Awal, A. S. Pio, M. J. Mim, P. K. P. Partha, Md. A. A. Kafi, and S. Farha, “A smart IoT-based hydroponics system for small-scale household in Bangladesh,” *Smart Agric. Technol.*, vol. 12, p. 101163, Dec. 2025, doi: 10.1016/j.atech.2025.101163.
17. S. Jain and M. Kaur, “Design and Implementation of an IoT-based automated EC and pH Control System in an NFT-based Hydroponic Farm,” *Eng. Technol. Appl. Sci. Res.*, vol. 14, no. 1, pp. 13078–13081, Feb. 2024, doi: 10.48084/etasr.6393.
18. A. S. Rathor, S. Choudhury, A. Sharma, P. Nautiyal, and G. Shah, “Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review,” *Heliyon*, vol. 10, no. 15, p. e34998, Aug. 2024, doi: 10.1016/j.heliyon.2024.e34998.
19. M. R. Hasan, Md. M. Rahman, F. Shahriar, Md. S. I. Khan, K. M. Mohi Uddin, and Md. M. Hasan, “Smart farming: Leveraging IoT and deep learning for sustainable tomato cultivation and pest management,” *Crop Des.*, vol. 3, no. 4, p. 100079, Nov. 2024, doi: 10.1016/j.cropd.2024.100079.
20. A. C. Austria, J. S. Fabros, K. R. Sumilang, J. Bernardino, and A. Doctor, “Development of IoT Smart Greenhouse System for Hydroponic Gardens,” *Int. J. Comput. Sci. Res.*, vol. 7, pp. 2111–2136, Jan. 2023, doi: 10.25147/ijcsr.2017.001.1.149.
21. J. Seetaram, A. Bhavya, C. Tarun, and V. Sameera, “Internet of Things (IoT) Based Greenhouse Monitoring and Controlling System Using ESP-32,” *IJARCCE*, vol. 13, no. 6, May 2024, doi: 10.17148/IJARCCE.2024.13605.

22. J. Saravanan, M. Rosmiati, S. Selvan, B. K. Ramesh, S. M. Prabhu, and S. K. Raju, “Integrating Internet of Things for Smart Hydroponics to Increase Productivity,” *Instrum. Mes. Métrologie*, vol. 24, no. 2, pp. 177–185, Apr. 2025, doi: 10.18280/i2m.240209.
23. W. Rofiansyah, F. R. Zalianty, F. A. La Ito, I. Wijayanto, H. H. Ryanu, and I. D. Irawati, “IoT-based control and monitoring system for hydroponic plant growth using image processing and mobile applications,” *PeerJ Comput. Sci.*, vol. 11, p. e2763, 2025, doi: 10.7717/peerj-cs.2763.
24. Ravindra B. Malabadi *et al.*, “Greenhouse farming: Hydroponic vertical farming- Internet of Things (IOT) Technologies: An updated review,” *World J. Adv. Res. Rev.*, vol. 23, no. 2, pp. 2634–2686, Aug. 2024, doi: 10.30574/wjarr.2024.23.2.2595.
25. A. Dsouza, L. Newman, T. Graham, and E. D. G. Fraser, “Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics,” *Agric. Syst.*, vol. 209, p. 103673, Jun. 2023, doi: 10.1016/j.agsy.2023.103673.
26. C. Y. Moreno-Aguilera, J. E. Botello-Álvarez, J. J. Martínez-Nolasco, J. A. Padilla-Medina, C. Martinez-Nolasco, and R. O. Herrera-Arroyo, “HYDROPONIC CULTIVATION EXPERIMENT MONITORED BY AN INTERNET OF THINGS SYSTEM,” *Agrociencia*, pp. 1–17, Oct. 2025, doi: 10.47163/agrociencia.v59i7.3430.
27. D. Zhou, R. L. Chretien, K. South, M. Evans, S. Lowman, and C. Mei, “Beneficial bacterial endophytes promote spinach plant growth under indoor vertical hydroponics,” *Technol. Hortic.*, vol. 4, no. 1, pp. 0–0, 2024, doi: 10.48130/tihort-0024-0012.
28. H. Y. Dasgan, S. Kacmaz, B. B. Arpaci, B. İkiz, and N. S. Gruda, “Biofertilizers Improve the Leaf Quality of Hydroponically Grown Baby Spinach (Spinacia oleracea L.),” *Agronomy*, vol. 13, no. 2, p. 575, Feb. 2023, doi: 10.3390/agronomy13020575.
29. B. Keskin, Y. Akhoundnejad, H. Y. Dasgan, and N. S. Gruda, “Fulvic Acid, Amino Acids, and Vermicompost Enhanced Yield and Improved Nutrient Profile of Soilless Iceberg Lettuce,” *Plants*, vol. 14, no. 4, p. 609, Jan. 2025, doi: 10.3390/plants14040609.
30. L. Li *et al.*, “The development of variable system-based internet of things for the solar greenhouse and its application in lettuce,” *Front. Plant Sci.*, vol. 15, Jan. 2024, doi: 10.3389/fpls.2024.1292719.