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SMARTGROW: AN ENERGY-AWARE SOLAR-POWERED IOT VERTICAL HYDROPONIC MONITORING AND AUTONOMOUS CONTROL SYSTEM

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Abstract:

With the increasing need for sustainable and resource-efficient food production, hydroponic systems have become popular for urban agriculture, particularly for the cultivation of vegetables and other plants, where the Internet of Things (IoT) technology is employed. There are currently many hydroponic platforms that are still connected to a grid power source and offer only partial integration of renewable energy, autonomous control, and remote monitoring in a single platform. These restrictions lower the operational sustainability, reduce deployment flexibility and require human intervention at all times. In this study, an energy-aware IoT vertical hydroponic monitoring and autonomous control system, called SmartGrow, is designed, developed, and implemented to enhance the cultivation efficiency, energy sustainability, and remote management of the system. The methodology proposed here uses a systematic engineering process with three major

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phases: system architecture design, hardware development, embedded software implementation, printed circuit board design, prototype fabrication and experimental validation. The microcontroller is an ESP32, which is equipped with pH, total dissolved solids (TDS), water level and light intensity sensors, and also automatically controls the nutrient pump, water circulation pump and grow light according to the set threshold values. The system also has an embedded HTML based web dashboard for in-situ monitoring and manual operation, a cloud based data logging system using Google Sheets, an instant alert notification system using Telegram and an energy subsystem powered by PV modules to enable energy aware operation. Experimental testing proved that sensors could be acquired, the threshold based actuator responses were reliable, data could be recorded continuously in the cloud, data could be monitored remotely and real-time alerts could be sent in the event of abnormal operating conditions. Combining renewable energy with automation via the IoT increases the system's autonomy and decreases reliance on traditional power sources. The proposed SmartGrow platform highlights the capability of developing a vertically integrated hydroponic system with renewable energy, intelligent sensors, autonomous control, and cloud-based monitoring, providing a viable and scalable solution for sustainable urban agriculture, educational purposes, and future smart agriculture projects.

Keyword:

Cloud-Based Monitoring; Energy-Aware Systems; Internet of Things; Solar-Powered Hydroponics; Vertical Farming

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Introduction

In addition to a rapidly growing urban population, the resulting pressures of climate change and reduction of arable land have put an additional pressure on finding more resource efficient and environmentally friendly alternative agricultural production systems. Limited land, water scarcity and climatic variations are limiting the conventional farming systems, leading towards the adoption of controlled environment agriculture (CEA) solutions. Vertical hydroponic systems stand out as one of the most promising methods due to several advantages they offer, such as maximizing space usage, conserving water, and enabling year-round crop production in a controlled environment (Azmi et al., 2024; Zulkifli et al., 2024).

In hydroponics, the plants can be cultivated without the presence of soil, with nutrients being directly supplied to the root zone, which improves nutrient uptake efficiency and consistency of crop yield. But the efficacy of hydroponic systems is highly reliant on environmental and solution parameter regulation, such as temperature, humidity, pH and water availability, among others. These variables, and many others, are hard to manage manually and frequently are not adequate to ensure optimal growth conditions. As a result, the use of the Internet of Things

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(IoT) technologies has grown significantly in recent years, allowing for hydroponic environments to be sensed, monitored, and controlled in real time (Suresh et al., 2024; Thakur et al., 2023).

While many important developments have been made, current hydroponic systems that utilize the Internet of Things (IoT) are still energy hungry and power dependent, and this can constrain their sustainability and deployment capabilities. This dependency is especially serious in urban micro-farming environments, and in remote areas where electricity is not always reliable. Recent studies have highlighted the need for integrating renewable energy sources, such as solar energy, to enhance system autonomy and minimize its operational carbon footprint (Erlangga et al., 2023; Rajendra, 2024). However, existing solutions typically address energy supply as an auxiliary, off-the-shelf component in isolation from the energy awareness being part of the control and monitoring framework of the system.

Therefore, for these limitations, this study aims to design an energy efficient vertical hydroponic monitoring and autonomous control system using solar energy in IoT. The system proposed combines renewable energy harvesting, real-time monitoring of the environment and intelligent automation in a single system. The strategy is integrated into system operations, which optimizes the conditions for optimal plant growth, and improves energy efficiency and system sustainability in the long term. This work helps towards building resilient, low carbon agricultural systems for urban farming and off-grid uses.

Literature Review

Initial investigations on the use of IoT technologies with hydroponic systems focused mainly on deploying low-cost sensors and basic automation to enhance the accuracy of the monitoring system and decrease the manual tasks. A study by Ullah et al. (2019) has shown the possibility of implementing the IoT technologies for real-time monitoring and management of hydroponic system. Although they were effective, they lacked intelligence and were not used to deal with energy efficiency issues.

Further studies further enhanced the functionality of the systems in terms of automatic environmental controls. Suresh et al. (2024) and Thakur et al. (2023) have designed and developed an indoor hydroponic system using IoT technology which monitors and controls various growth parameters using rule-based automation. While these solutions helped ensure that the operations were reliable, they still relied on traditional power sources, limiting the potential for sustainability.

Later work has focussed on modular and scalable architectures in order to improve the adaptability of the system. Tomičić et al. (2022) presented a modular architecture for a grow room based on IoT communications for flexible deployment, and Bua et al. (2024) presented a compact design for a smart hydroponic greenhouse. Although these systems have great architectural features, they are not widely considered for energy-aware operation or integration of Renewable Energy.

The application of machine learning and artificial intelligence in predictive control and optimization has also benefited the intelligent agriculture sector. Wang (2024) and Bulut and Hacıbeyoğlu (2024) have shown the promising possibilities of data-driven approaches to improve the greenhouse performance. However, these methods can be energy and computation intensive, which is not ideal for power-constrained or off-grid applications.

In the past few years, researchers have begun to focus on sustainability incorporating renewable energy. Erlangga et al. (2023) proved that Solar-powered IoT architectures can be applied to agriculture applications. However, current research often focuses on energy harvesting as an external unit and not integrating energy awareness into the hydroponic control system.

On the contrary, the current study uses a holistic system design approach in which the solar energy harvesting, the real-time monitoring using IoT, the autonomous control, and the vertical hydroponic farming are integrated and implemented under an energy-aware approach. The proposed system tackles some of the identified challenges in previous studies, making it a promising step toward sustainable and intelligent agriculture.

A structured review of existing studies is performed to gain a thorough understanding of the current state of the art and to systematically identify the gaps in existing knowledge of hydroponic systems based on IoT. The identified literature is analysed in terms of the main features such as system architecture, the level of automation, energy dependency and sustainability issues. Table 1 is a representative comparison of works that summarizes the key features and limitations of each. The comparative analysis suggests that there are certain gaps in the research that need to be addressed, such as energy-efficient operations, integration of renewable energy sources, and autonomous management of vertical hydroponic systems, which serves as a compelling motivation for the research proposed.

Table 1: A Comparative Summary of Representative Works

Study	System Focus	Limitations Identified	Research Gap
Ullah et al. (2019).	IoT-based hydroponic monitoring and basic control using low-cost sensors.	Focuses on monitoring accuracy only; no autonomous decision-making; fully grid-dependent.	Lacks energy-aware design and renewable energy integration for sustainable operation.
Tomičić et al. (2022)	Modular IoT micro-grow room architecture with a scalable design.	Emphasizes modularity but omits energy optimization and renewable power sources.	Does not integrate solar energy or energy-aware operational control.
Thakur et al. (2023)	Comprehensive IoT monitoring and rule-based control for hydroponics.	Automation is limited to predefined rules and relies on a conventional power supply.	No consideration of system energy efficiency or autonomous energy management.
Suresh et al. (2024).	Automated indoor hydroponic farming with real-time IoT sensing.	Improved automation but lacks renewable energy support and energy-aware scheduling.	Energy sustainability is not embedded into system design.

International Journal of Innovation and Industrial Revolution IJIREV
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Erlangga et al. (2023)	Solar-powered IoT architecture for smart agriculture.	Renewable energy is treated as an auxiliary subsystem in a limited vertical farming context.	Energy awareness is not integrated into hydroponic control logic.
Bua et al. (2024).	Modular smart hydroponic greenhouse system.	Focuses on compact design; energy source and consumption are not analyzed.	No energy-aware or autonomous energy optimization framework.
Wang (2024)	Intelligent greenhouse control using IoT and machine learning.	High computational and energy demand; less suitable for off-grid systems.	Requires an energy-aware framework to balance intelligence and power efficiency.
Zulkifli et al. (2024)	Intelligent IoT-based vertical farming for food security.	Focus on monitoring and automation; the energy source is not explicitly addressed.	Renewable energy integration and energy-aware control are absent.

Methodology

This methodology provides a systematic design and implementation of an energy-aware smart farming system for vertical hydroponic cultivation which uses solar power and is monitored and controlled by an IoT system. It will monitor and control various key growth parameters of plants, such as pH, total dissolved solids, water level and light intensity. It provides an overview of the system design, hardware setup, sensor integration, software development, and the flow of operations. It also outlines the creation of a web-based monitoring system which allows for the visualization, control and remote parameter setting of actuators in real time. The methodology provides reliable operation, energy efficiency and effective control for sustainable hydroponic farming applications.

System Design and Operation

The integrated architecture of the proposed IoT-enabled hydroponic monitoring & control is shown in Figure 1, where each subsystem is interconnected. The architecture's key component is the ESP32 microcontroller, acting as the main computing and decision-making powerhouse. The ESP32 has a built-in Wi-Fi and enough processing power to gather data from multiple sensors, perform control algorithms, and communicate both ways with the outside world.

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IJIREV
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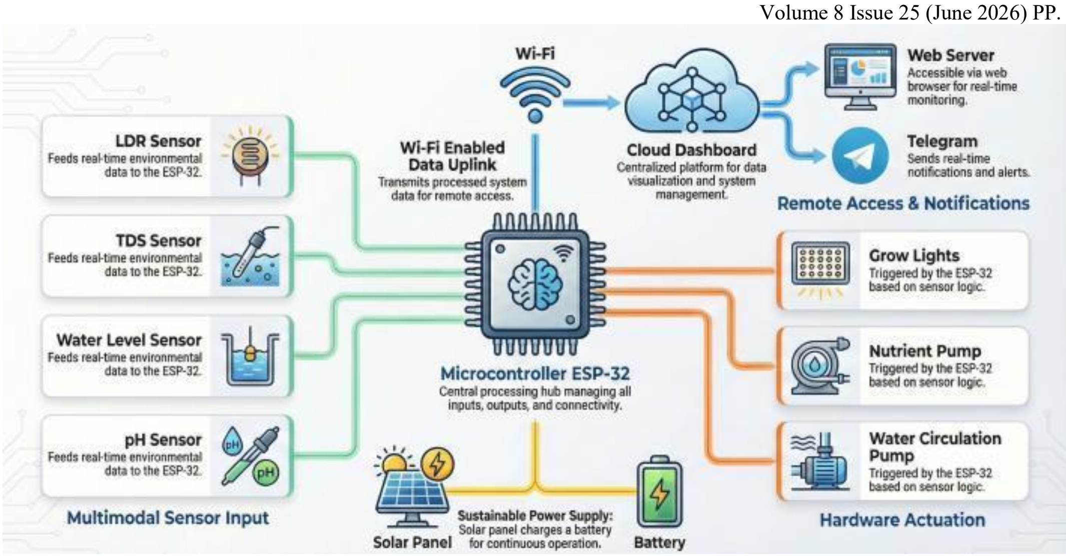

Figure 1: SmartGrow Control System Architecture (Generated by NotebookLM)

The microcontroller is connected to four main sensors which collect important cultivation parameters. The pH sensor monitors the nutrient solution acidity or alkalinity to keep plant roots at the proper chemical level. The Total Dissolved Solids (TDS) sensor measures the amount of nutrients in the solution, which is an indirect measure of its strength. A water-level sensor is attached to the water reservoir to avoid pump dry runs and ensure pump system reliability. Besides, it is fitted with a Light-Dependent Resistor (LDR) sensor to sense the ambient light intensity allowing adaptive lighting control. The multimodal inputs allow the system to continuously monitor the environmental and nutrient-related parameters which are crucial to the growth of hydroponic crops.

Acquired data is locally processed on ESP32 and uploaded to a cloud-based dashboard through Wi-Fi. This cloud platform acts as a single data source and visualization tool offering real-time trend and system status visuals to end users. Web server integration means that the system is accessible via the web browser and linkage with Telegram allows receiving instant notifications when predefined thresholds are exceeded. This type of communication system helps to monitor and intervene in cultivation as needed, without needing to be physically on site.

The architecture not only monitors but also includes automatic actuation mechanisms. The ESP32 is programmed with the logic for decision making, and sensor feedback, and can then manipulate the grow lights, nutrient dosing pump, and water circulation pump. This is a closed loop control system which allows for dynamic responses to environmental conditions, delivery of consistent nutrients, and improved overall plant growth performance.

A power subsystem using solar power supplies energy autonomy. The photovoltaic (PV) panel stores energy in a battery unit, which is then connected to the microcontroller, sensors, and actuators. This renewable energy setup helps in lowering the reliance on electrical supply from the grid and in facilitating roll-out in areas where infrastructures are scarce.

International Journal of Innovation and Industrial Revolution
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IJIREV
Volume 8 Issue 25 (June 2026) PP. 491-513

The overall design showcases a seamless blend of embedded control systems, wireless communication, real-time analytics, and energy efficiency, highlighting the integration of these technologies. The system design is implemented according to the principles of smart agriculture, and it is an automatic, expandable system for precision hydroponic cultivation.

Operational Logic

The operational logic of SmartGrow (see Figure 2) is designed in such a way that it guarantees the reliability of the sensing, the adaptive control and the effective use of energy. It starts with system initialisation which checks the availability of battery power, wireless connection and the status of the server. When communication and system readiness are confirmed, the controller checks to see if automatic mode is enabled. This action then determines the control path of the next control unit, and either autonomous control or user control is possible.

If automatic mode is on, the controller will first compare the concentration of the total dissolved solids (TDS) in the nutrient solution to preset levels. When the concentration is within the acceptable range, the water pump is turned on so as to provide water circulation and keep the solution homogeneous. If the value is below the lower limit, a correcting series is started: the water pump is activated for a certain time and is later complemented by short-term activation of the nutrient pump for concentration balancing. On the other hand, when the concentration is above the specified limit, it gives a high-TDS alert message through Telegram, and the water pump will turn on to reduce the concentration. This staged response approach helps to avoid sudden nutrient fluctuations and to ensure stable nutrient management.

Once the nutrient assessment is completed, the system determines the level of the reservoir by measuring the distance. If the measured value is above the safety margin, then a notification alert is sent as a warning of potential depletion. The intensity of light is measured with the light dependent resistor (LDR) sensor. When light levels are low and it is in the cultivation time window (6 AM to 6 PM), the grow light will turn on to provide additional light for photosynthesis. If not, the lighting system is inactive in order to conserve energy. The pH is then tested to ensure that it is within the range of optimum growth. Any variation from the acceptable range activates an alarm, which will prompt to take corrective action.

The system parameters and actuator states are captured at the end of each control cycle to monitor and analyse the system performance. If automatic mode is turned off, the system enters manual mode and the nutrient pump, water pump and grow light can be turned on and off by the user. All actions are written before the system again evaluates the operational status and re-enters the monitoring loop. The structured logic incorporates energy-aware actuation, notification systems, and threshold-based decision-making, ensuring stable operation, adaptive responses, and sustainable resource management within the SmartGrow platform.

International Journal of Innovation and Industrial Revolution
IJIREV
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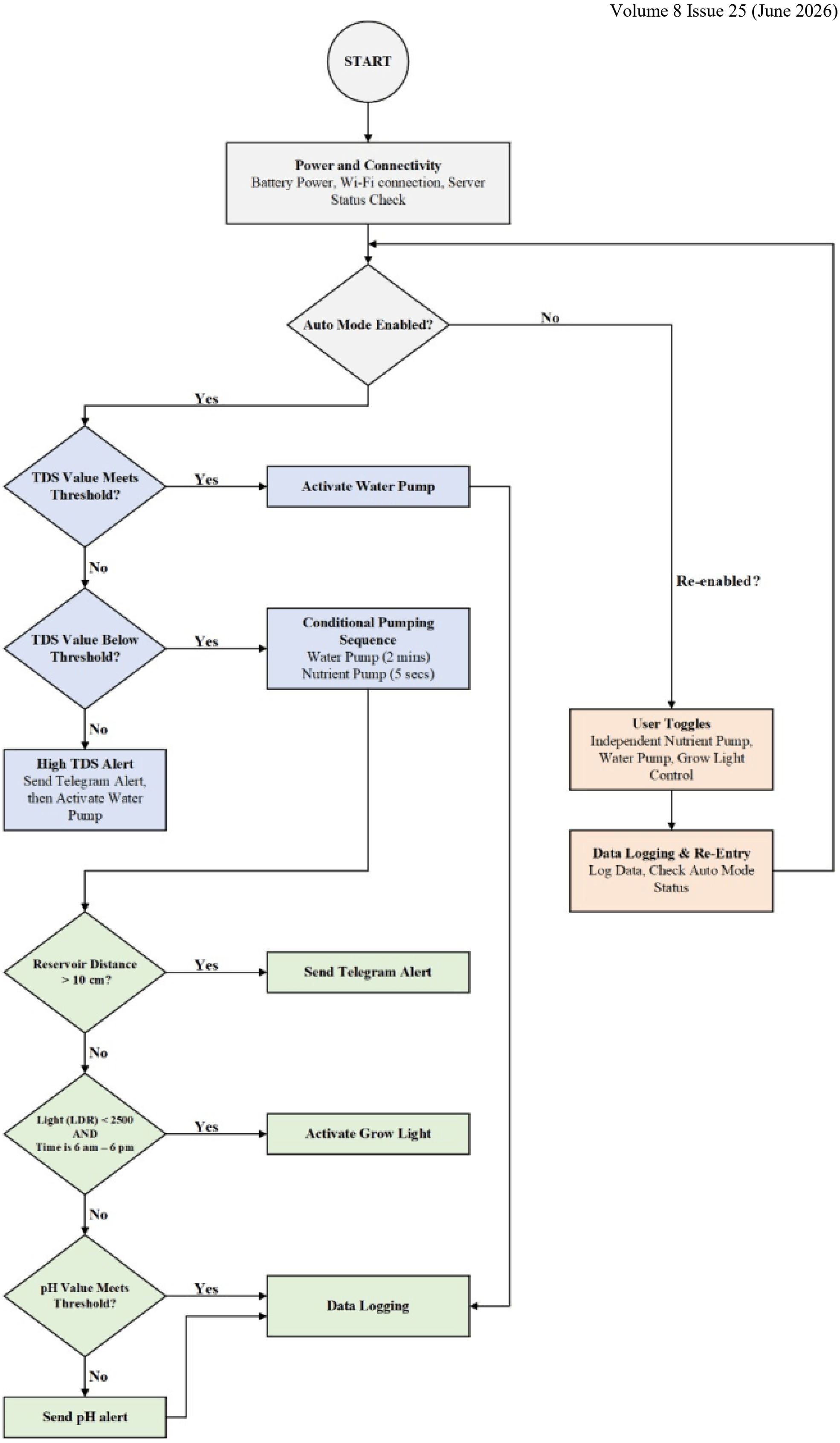

Figure 2: The Operational Logic of SmartGrow

International Journal of Innovation and Industrial Revolution
IJIREV
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Circuit Schematic and Printed Circuit Board Design

The schematic of the SmartGrow system is shown in Figure 3 and includes the interconnections between the sensors, the control logic and the actuators. The ESP32 microcontroller is the heart of the design, serving as the communication and processing power. The microcontroller is connected to several sensors such as TDS, pH, ambient light (using LDR), and ultrasonic sensor module for reservoir level. To allow for time-based control of the lights, a time module has been added that is connected to the outside. A current limiting resistor, an indicator LED, etc. are provided as supporting components for stable signal conditioning and to display its condition.

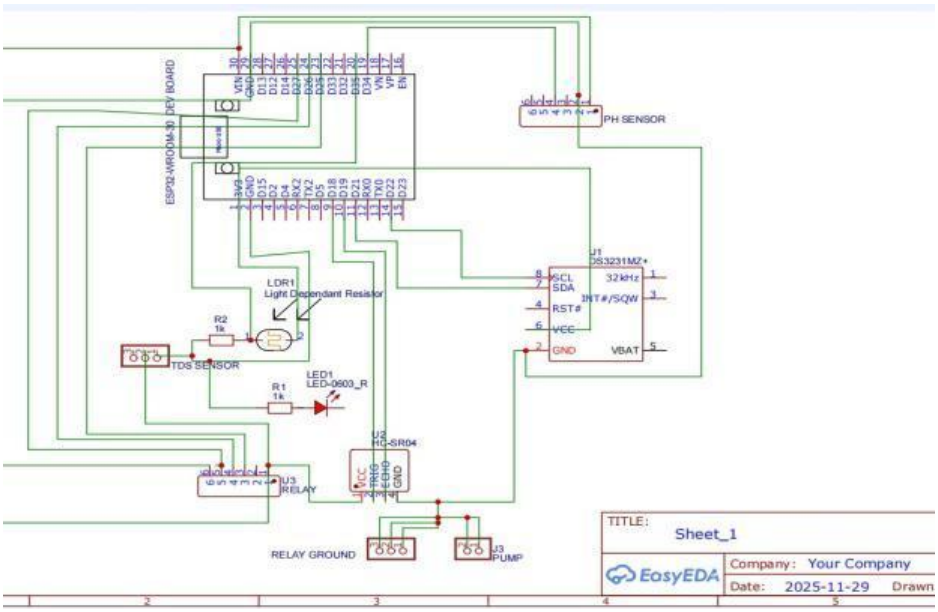

Figure 3: The Schematic of The SmartGrow

The relay driver circuit controlling the various pumps such as a nutrient and water pump is also shown on the schematic. The relay module helps protect the low voltage logic domain from high current actuator circuits to increase system reliability and safety. Power connections are made to provide regulated power to sensing devices, control devices and to provide a common ground reference. The overall schematic shows a well-organized layout of the sensing, timing, actuation and communication components, which collectively contribute to form a coherent embedded control system for real-time monitoring and autonomous control within the framework of the SmartGrow platform.

SmartGrow's corresponding printed circuit board layout is shown in Figure 4, which is based on the circuit schematic in Figure 3. The layout implements the conceptual interconnection in the schematic with a hardware implementation that is compact, integrated and shows all the interfaces to the sensors, control circuits, communication modules and power distribution on a single board. The ESP32 microcontroller is placed in the middle to simplify the routing and minimize the length of analog/digital paths. The pH sensor, total dissolved solids sensor, light-dependent resistor and reservoir-level sensing module are all connected via dedicated connectors resulting in organized, reliable signal acquisition. In order to keep electrical noise to a minimum and to ensure the accuracy of the measurements, analog traces are separated from high current switching lines from the actuator controlled by relays.

International Journal of Innovation and Industrial Revolution
IJIREV
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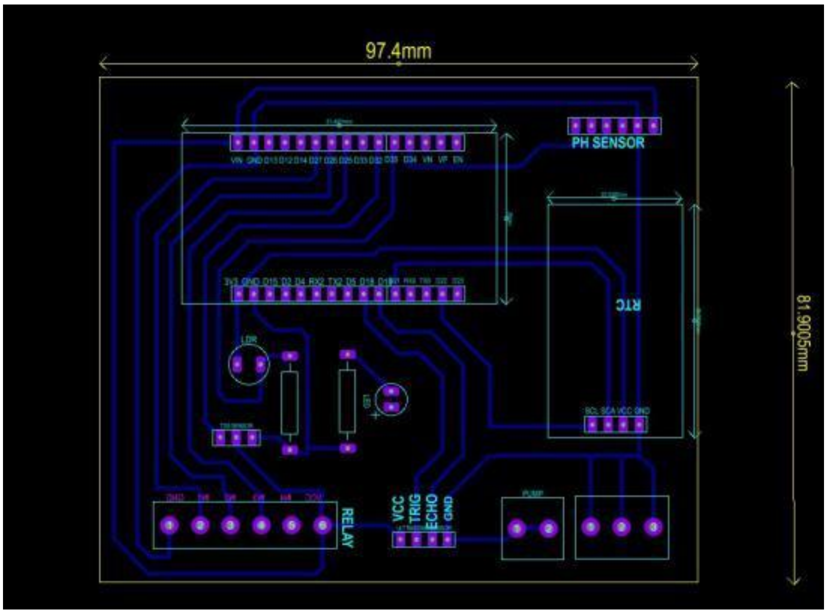

Figure 4: The Printed Circuit Board Layout for SmartGrow

The actuator control section, including the nutrient pump, water pump and grow light relay outputs is positioned around the board edges to allow for wider traces for higher current output and ease of external wiring connections. Power input and regulation circuits are designed to provide stable voltage from the battery and solar charging circuits to both logic-level circuits and loads. The distinction between low voltage control signals and higher voltage and current actuating lines provides for improved operating stability and interference avoidance. Overall, the PCB layout is the result of a careful approach to the hardware integration, designed to ensure signal integrity, current carrying capacity and maintainability of its components, which in turn facilitates the energy-aware and autonomous control functions of the SmartGrow system.

Hardware Implementation

The SmartGrow system prototype assembly is shown on a breadboard platform in Figure 5, for preliminary validation and functional testing. This setup was employed to test the ESP32 microcontroller with the sensors, actuators, and communication modules prior to printed circuit board assembly. The ESP32 is the main processing unit that connects to the ultrasonic sensor for determining the reservoir level, the pH sensor module, and other environmental sensors. The breadboard setup allows for quick modification of circuit connections and flexible routing of signals, making for ease of sensor calibration and testing the performance of controls under simulated operating conditions.

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 8 Issue 25 (June 2026) PP. 491-513

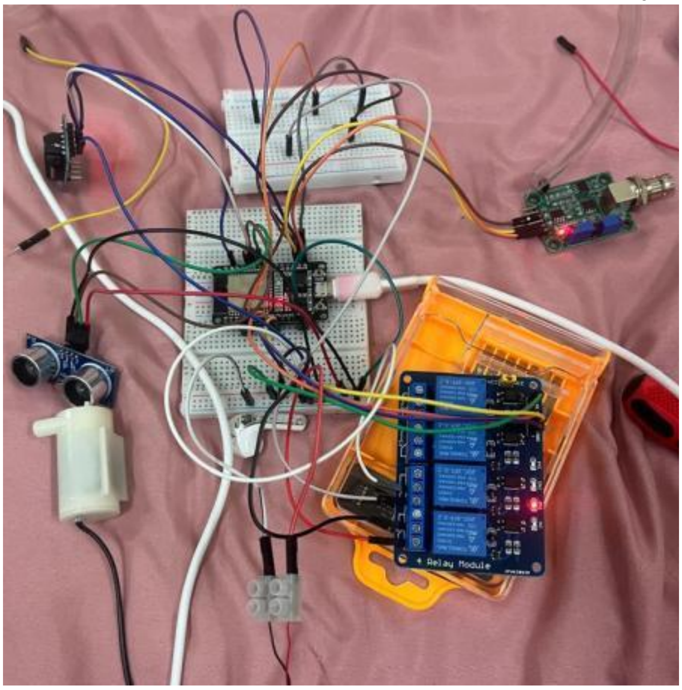

Figure 5: The Prototype Assembly of The SmartGrow Constructed on a Breadboard

The relay module is connected to the microcontroller for the purpose of switching external loads such as the nutrient pump, water pump and grow light. To keep the circuit safe and stable during operation, there was a logical separation between low voltage control circuits and high current actuator paths during prototyping. Power distribution lines were arranged to deliver a uniform power supply to all the sensing and control elements during testing. This experimental setup was an intermediate step where the functionality of the system, communication reliability and responsiveness of the actuators were tested prior to the final printed circuit board version.

Prototype Development

The developed prototype of SmartGrow is presented in figure 6, which aims to be a compact system to validate the vertical hydroponic system with embedded sensor, automated control and renewable energy system. The physical design is a vertical planting column attached to a nutrient reservoir, which creates a space efficient design for controlled environment culture. There are several planting ports throughout the column for efficient use of vertical space. Meanwhile, a specific grow light is mounted on a dedicated lighting pole in close proximity to the structure with enough light to provide supplemental lighting in a controlled environment.

Figure 6: The Developed SmartGrow Prototype

The design of the prototype includes pH, TDS, water level inside the reservoir and ambient light sensing. The sensors gather continuous environmental/ nutrient solution data and the microcontroller monitors these data and operates the actuators in accordance with a set of control thresholds. The actuation subsystem consists of a water pump for moving the nutrients, a dosing pump for adjusting their concentration and a grow light controlled depending on the ambient light and programmed operating times. The system can be controlled either automatically or manually from a web-based interface, where users can view real-time parameters and can take manual control of the system if necessary.

The building is also equipped with a photovoltaic panel, which is integrated into the structure to generate renewable energy and contribute to the energy efficiency of the building. The position of the solar module and lighting supports are based on energy capture and practical considerations of structural balance. The prototype is generally able to demonstrate success in hardware integration, functional stability, and operational responsiveness. The developed system proves the possibility of creating an energy conscious, IoT supported vertical hydroponic system, which can be used in small scale cultivation in urban areas and educational implementation, as well as an energy saving smart agriculture application.

Result and Discussion

This Results and Discussion section is divided into three key subsections: Design and Implementation of the Embedded Web Dashboard, Cloud-Based Data Logging and

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 25 (June 2026) PP. 491-513

Performance Monitoring, and Real-Time Remote Alert and Notification System. The subsections provide the functional validation and performance evaluation of the proposed SmartGrow system and its use with respect to the monitoring capabilities, data management framework, and remote supervisory capabilities within an integrated system that is part of the IoT-enabled hydroponic platform.

Design and Implementation of the Embedded Web Dashboard

The SmartGrow dashboard is realized as a light-weight web page created in standard HTML and served straight from the ESP32 through a built-in web server, as shown in Figure 7. This is done by the microcontroller creating the entire HTML file dynamically and sending it to the browser when it requests it over the local network address. The structure of pages follows the basic format of HTML: containers for grouping content, form elements for user interaction and a heading for the dashboard's title. The concept makes the interface entirely stand-alone, as it resides in the device firmware—no external hosting required, and the interface loads quickly on pages, and is always available as it's running. In general, the HTML-based design ensures a lightweight, yet functional user interface suited to resource-constrained IoT devices, with rapid page-load time, cross-device compatibility, and a convenient platform for monitoring and manual operation.

Figure 7: HTML Coding to Develop SmartGrow Dashboard

The SmartGrow dashboard's graphical user interface is shown in Figure 8 and serves as the main interface for monitoring and controlling the hydroponic system in real time. Current sensor data, total dissolved solids, water level, light intensity and pH are shown in the top part of the dashboard. Every parameter is displayed in a well-structured panel to allow a quick overview of the system. Also, key actuators like the nutrient pump, water pump, grow light and system mode are shown, providing the user with the status of the system.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 25 (June 2026) PP. 491-513

Figure 8: SmartGrow Dashboard

Another section of the dashboard is the threshold configuration, which enables the user to set lower and upper limits for nutrient concentration and pH. These set points are fed directly into the control logic and act as system set points, allowing the system to be controlled adaptively without firmware changes. There are manual control buttons beneath these sections to switch on or off the nutrient pump, water pump and grow light. There is also a reset function that will put the system back into automatic mode. In general, the dashboard combines monitoring and manual override functions in a single interface, allowing for an autonomous control mode and manual mode if needed.

The dashboard validation illustrates that validation is possible in real time and users can interact with the dashboard efficiently using an embedded web server without the need for external hosting. The sensors and actuators were updated continuously during the test and the user could see the behaviour of the system and intervene accordingly if needed. It shows that the embedded dashboard is an effective human–machine interface with a lightweight computation requirement of the ESP32 platform. The proposed architecture in comparison with cloud dependent dashboard architectures from previous studies is simpler and less expensive for resource constrained IoT applications.

Cloud-Based Data Logging and Performance Monitoring

The cloud data-logging interface that was developed for the SmartGrow system in Google Sheets is shown in Figure 9. The embedded controller transmits real-time sensor measurements and system operational states to Google Sheets during normal operation and testing, which act as a central repository. The records are automatically timestamped to maintain the chronological order and to facilitate the tracing of the system's responses. The logged parameters include total dissolved solids, water level, light intensity, and pH, as well as the operational status of the nutrient and water pumps and the grow light. The data collected during the testing phase showed changes in TDS concentration, water levels in the reservoir, light intensity, and pH, depending on the set thresholds and manual actions taken by the system.

International Journal of Innovation and Industrial Revolution
IJIREV
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1	TIMESTAMP	TDS	WATER LEVEL	LDR	pH	NUTRIENT PUMP	WATER PUMP	GROW LIGHT
1461	2026-1-5 16:07:48	2418.89	2.38	2304	6.77	OFF	ON	OFF
1462	2026-1-5 16:08:01	2418.89	2.7	2002	6.77	OFF	ON	OFF
1463	2026-1-5 16:08:17	145.9	2.38	1091	12.33	ON	ON	ON
1464	2026-1-5 16:08:31	415.03	2.38	1090	12.98	OFF	ON	ON
1465	2026-1-5 16:08:44	473.74	2.69	1041	6.77	OFF	ON	ON
1466	2026-1-5 16:08:58	409.33	2.7	1060	13.8	OFF	ON	ON
1467	2026-1-5 16:09:10	421.4	2.38	1089	10.61	OFF	ON	ON
1468	2026-1-5 16:09:28	140.94	2.7	1119	12.55	ON	ON	ON
1469	2026-1-5 16:09:41	446.45	2.7	1122	8.99	OFF	ON	ON
1470	2026-1-5 16:09:55	432.69	2.7	1127	12.12	OFF	ON	ON
1471	2026-1-5 16:10:07	414.08	2.7	1166	12.31	OFF	ON	ON
1472	2026-1-5 16:10:24	446.78	2.11	918	11.94	OFF	ON	ON
1473	2026-1-5 16:10:38	137.72	2.06	569	12.91	ON	ON	ON
1474	2026-1-5 16:10:51	572.27	2.38	1120	13.2	OFF	ON	ON
1475	2026-1-5 16:11:05	567.55	2.38	1058	12.64	OFF	ON	ON
1476	2026-1-5 16:11:17	538.75	2.7	1038	12.52	OFF	ON	ON
1477	2026-1-5 16:15:05	2418.89	2.38	1307	6.77	OFF	ON	ON
1478	2026-1-5 16:15:18	2418.89	2.38	3461	6.77	OFF	ON	OFF
1479	2026-1-5 16:15:33	2418.89	2.38	3055	6.77	OFF	ON	OFF
1480	2026-1-5 16:15:47	2418.89	2.38	2821	6.77	OFF	ON	OFF
1481	2026-1-5 16:16:22	2418.89	4.93	1681	9.47	OFF	ON	ON
1482	2026-1-5 16:16:37	2418.89	0	1695	9.47	OFF	ON	ON

Figure 9: The Cloud-Based Data Logging Interface Implemented using Google Sheets

The data collected during test is used to show the dynamic behaviour of the automation logic. For example, the TDS and pH levels were found to be correlated with the activation of the nutrient and water pumps. Meanwhile, during specific periods of time, the light intensity was changed causing the grow light to change its operational condition. The observed response of the actuators and stability of the control system is clearly shown with these time-stamps, which also enables experimental assessment of the system's response to different environments. These sensors and actuators are logged continuously, giving possibilities for performing a retest of the system or for evaluating the accuracy of the control. The cloud-based logging mechanism therefore enables the following of the system from a distance and generates a reliable dataset, which is suitable for testing the system functionality and operational efficiency during the experimental validation phase.

The cloud-based logging mechanism is a demonstration of the capability of the proposed system to store the entire operational history for analysis and performance evaluation. The embedded controller will continuously record timestamped measurements of the sensors and the state of the actuators, ensuring that the data is communicated safely from the embedded controller to cloud services. Historical data is especially useful for detecting trends in operations, diagnosing abnormal operations, and predictive analytics. The advantages of the cloud-based approach over traditional standalone systems include better traceability and the ability to manage hydroponic cultivation based on data.

Real-Time Remote Alert and Notification System

Figure 10 displays an example of the Telegram alert notification system which is part of the SmartGrow platform and is designed to alert users in real-time as soon as an anomaly is detected. This message feature will be enabled if monitored parameters are found to be out of the normal operating range. An alert is automatically created and sent to users using a Telegram bot, which means that they do not have to connect to the web dashboard. Specific information about the parameters, including the levels of total dissolved solids (TDS), pH deviation, and

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 25 (June 2026) PP. 491-513
reservoir water level, is included in the notifications, as well as the measurement value at the time of the detection.

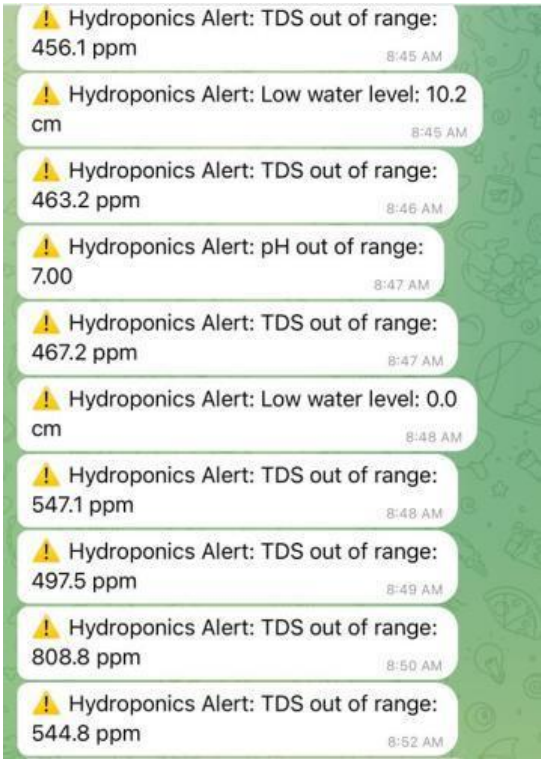

Figure 10: The Telegram Alert Notification

This alert function improves the responsiveness of the system by allowing critical changes in concentration of nutrients and/or water availability to be communicated in a timely manner. During testing, when total dissolved solids readings were out of the acceptable limits, pH readings were out of the optimal limits, and reservoir levels were showing possible depletion, alerts were issued. A messaging-based notification layer enhances the overall monitoring capabilities by extending monitoring beyond the scope of the local network. This allows for constant monitoring, minimizes the possibility of system imbalance occurring for extended periods of time, and allows for system intervention when needed in a timely manner for operation.

Importantly, the notification system makes the SmartGrow platform more usable on the ground, beyond the local monitoring interface. Transmission of abnormal operating conditions immediately allows for corrective action to be taken before exposure to unsuitable environmental conditions causes abnormal plant growth. This capacity will bring operation reliability and decrease the necessity of manual inspection, which is more suitable for the proposed system to be used in urban farming and small-scale commercial hydroponic production.

Performance Evaluation of SmartGrow

A series of functional tests was also performed in order to test the functionality of the proposed SmartGrow platform with the focus on the sensor operation, the responsiveness of the actuators, the cloud connection, reliability of data logging and the performance of remote

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 25 (June 2026) PP. 491-513
notifications. This evaluation was conducted to ensure the embedded control system was stable under normal operation conditions, and not for comparing crop productivity. The monitoring and control system were fully operational during the experiments, with no disconnection between the various components of the system (sensing modules, ESP32 controller, cloud platform, and actuator subsystem). The overall experimental performance of the developed system is summarized in Table 2.

Table 2: Experimental Performance of SmartGrow

Performance Parameter	Experimental Observation	Performance
pH sensor operation	Stable measurement throughout testing	Successful
TDS sensor operation	Continuous monitoring with consistent readings	Successful
Water level sensor	Reliable detection of the reservoir level	Successful
LDR sensor	Correct detection of ambient light intensity	Successful
Water pump control	Activated according to predefined logic	100% successful
Nutrient pump control	Operated correctly when the TDS threshold was violated	100% successful
Grow light control	Automatically switched according to light intensity and schedule	100% successful
Embedded web dashboard	Continuous real-time display without interruption	Stable
Google Sheets logging	Timestamped sensor data is stored continuously	No missing records observed
Telegram notification	Alerts successfully delivered during abnormal conditions	Successful
Overall system operation	Continuous autonomous operation during testing	Stable

The experimental results shown in Table 2 verify the normal functioning of all the sensing, communication and control modules during the testing. The ESP32 was able to receive sensor data and perform the threshold based control algorithm without communication failure and controlled the operation of the actuators. At the same time, the data collected by the sensors was sent to the embedded web dashboard for real time viewing and stored in Google Sheets for long term monitoring and performance analysis. If the conditions were not normal, the Telegram notification service informed the users immediately, thus allowing for quick action.

These results show the feasibility of achieving stable and coordinated operation of various IoT components using the proposed system. The synchronization of the sensing, decision-making, cloud communication and remote notification successfully shows that the designed platform is capable of supporting autonomous hydroponic monitoring with a little bit of human effort. Multiple services being integrated into a single embedded platform also helps lower the operational complexity and enhances system reliability.

SmartGrow is different from many other hydroponics systems reported in literature, which focus mainly on the environmental monitoring and/or the control of the actuators with the help of rules and logic (Thakur et al., 2023; Suresh et al., 2024), because it combines renewable energy, cloud-based monitoring, automatic control of the actuators, continuous logging of data, and instant notification by a mobile app. This integration facilitates greater autonomy in operations and gives users ongoing supervision, away from the local cultivation setting.

In the context of smart agriculture, the platform proposed in this paper shows the feasibility of integration of renewable energy, embedded intelligence, cloud services, and wireless communication in a compact vertical hydroponic system. This integration is crucial for sustainable urban agriculture, as it minimizes the need for labor-intensive management and optimizes the use of resources, enhances operational efficiency, and facilitates better decision-making processes with access to real-time data.

Performance Metrics of the Proposed SmartGrow System

During the experimental validation, several quantitative performance metrics were assessed in order to further evaluate the operational performance of the proposed SmartGrow system. These measurements can be used to objectively assess the system's sensing, communication, control, and data management functions. Table 3 summarizes the key operational indicators that are the basis for the performance evaluation. The key operational indicators for the performance evaluation are summarized in Table 3. The dashboard refresh interval of around 2 seconds allowed for real-time monitoring and provided seamless interaction between the embedded controller and the web interface.

The cloud-based monitoring framework also showed very good performance, with 1,482 experimental records being uploaded to Google Sheets without a single missing record or synchronization failure. During the validation of the hardware-software integration, the developed prototype also showed continuous operation without interruption for 2 hours.

Table 3: Performance Metrics of the Proposed SmartGrow System

Performance Metric	Result
Functional test success rate	100% (10/10 tests passed)
Dashboard refresh interval	2 s
Data logging success rate	100% (1,482 records logged without missing entries)
Continuous system operation	2 h without interruption

These performance metrics show that the proposed SmartGrow platform offers reliable monitoring, timely control of actuators and supervise control remotely in a single IoT platform. Unlike most other hydroponic monitoring platforms available today, which are mostly concerned with acquiring sensor information, the proposed platform combines embedded web monitoring, cloud-based data logging, renewable energy, and instant mobile notifications into one architecture. Such integration can provide better data access, improve the reliability of the

International Journal of Innovation and Industrial Revolution
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operations and aid in better and efficient decision making for sustainable smart agriculture applications.

Conclusion

A SmartGrow, an energy-efficient and solar-powered monitoring and control system for IoT vertical hydroponic farming technologies to enable sustainable and autonomous crop farming, was presented in this paper. A systematic engineering approach was used that involved designing the system architecture, developing embedded hardware and software, integrating renewable energy, setting up an online monitoring system, cloud data logging, and experimental testing. The constructed platform was able to combine the functions of sensing pH, TDS, water level and light intensity and controlling the autonomous actuators, thereby realizing the continuous monitoring and intelligent regulation of hydroponic operating conditions. The acquired results from the experimental evaluation showed that the proposed framework was stable in terms of sensor acquisition, reliable in terms of actuator operation, continuous data logging on the cloud, and responsive real-time notification on the embedded web dashboard and Telegram alert system.

This study proposes a practical approach to combine renewable energy, embedded intelligence, cloud supervision and autonomous control in a small-scale hydroponic system rather than developing a new prototype. The results give empirical evidence the energy-aware system integration can enhance the operational resilience, lessen reliance on conventional power sources, and enable uninterrupted remote monitoring without system complexity. The integrated design framework provides a practical guideline for future work on IoT-based energy-aware smart agriculture systems and serves as a stepping stone towards scaling up energy-aware IoT designs for the larger-scale challenges and requirements of precision agriculture.

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