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RESEARCH ARTICLE

SENSOR-GUIDED SMART GREENHOUSE SYSTEM FOR OPTIMIZED CROP PRODUCTION USING ESP32 MICROCONTROLLER

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Abstract

Greenhouse agriculture plays a key role in boosting crop yields and quality. Still, many current setups struggle with accurate control over environmental factors [1]. This paper outlines an IoT-driven smart greenhouse setup. It relies on the ESP32 microcontroller to handle key parameters like temper- ature, humidity, light levels, and soil pH automatically. The ESP32 comes with Wi-Fi and Bluetooth built in, allowing data to flow in real time to the ThingSpeak cloud for oversight and adjustments [2]. Sensors such as the DHT11 for air conditions, soil moisture detectors, light-dependent resistors, and pH probes gather the needed environmental details. Actuators including DC fans, water pumps, and LED lights then keep conditions ideal for growth. Automation and cloud links help manage resources well and support ongoing production. The approach adds to smart farming practices overall. It provides a model that scales easily, costs little, and works efficiently for better greenhouse operations [3].

Introduction:-

From very early times, agriculture has been the very foundation of human civilization, providing food, economic sustainability, and cultural identity for generations. Yet, in its traditional setup, farming grows commonly into an extremely challenging activity, because of climate variations, soil degra- dation, and resource mismanagement. These issues have led researchers and practitioners alike to investigate on what may be the best innovative practices that can boost productivity while promoting sustainability. Among such alternatives is the promising arena of greenhouse farming, wherein they provide controlled environments to shield the crops from external threats, including pests, extreme temperatures, and erratic rainfall [5]. Greenhouses facilitate year-round crop cultivation and func- tion as buffer zones against erratic climatic conditions. Nev- ertheless, conventional greenhouse systems are often labor intensive, prone to human error, and inefficient due to heavy reliance on manual monitoring and intervention. Of utmost importance to maintaining plant health and yield is the control of temperature, humidity, soil moisture, and light intensity. Very often, manual control of these parameters offers ill- prepared maintenance, thereby leading to irrelevant discrep- ancies with overuse or wastage of resources [6]. Thus, the precision and automation of greenhouse management have become an increasingly relevant issue. In recent years, the integration of Internet-of-Things (IoT) technologies in agriculture has brought forth a complete rev- olution concerning the monitoring and controlling of environ- mental parameters. IoT interconnects many objects equipped with sensor data, which are able to transmit and accept data in real time so that automated decision-making processes and remote monitoring can be set up [7]. This creates what is often termed an era of smart farming, which is made possible by interfacing sensors, actuators, and microcontrollers to create mechanisms capable of maintaining optimum conditions for crop production, requiring little or no human involvement. The ESP32 microcontroller has emerged in smart agricul- tural applications because it is one of the low-cost hardware designs that brings flexibility, as well as wireless commu- nications built in. It possesses a dual-core processing unit, low power consumption, and several input/output pins to accommodate some complex tasks involving sensor data ac- quisition, actuator control, and cloud integration [9]. Its built- in Wi-Fi and Bluetooth modules allow easy interfacing with cloud platforms, fostering remote monitoring and control of greenhouse systems. This study introduced a sensor-guided smart greenhouse system that relied mainly on the ESP32 microcontroller and aimed at automating the regulation of specific environmental parameters.

The sensor array included the DHT11 for tem- perature and humidity, soil moisture sensors, light-dependent resistors (LDRs), and pH probes to monitor the greenhouse environment in real time. Actuators such as DC fans, water pumps, and LED grow lights respond dynamically to sensor inputs, ensuring that conditions remain within optimal ranges for plant growth [1]. The data coming from the sensors would then be sent into the ThingSpeak platform, which would allow visualization, storage, and analysis of the data. Among the innumerable services offered by ThingSpeak is a friendly interface with which the user can monitor environmental trends, set thresh- olds, and trigger automatic actions [2]. This makes it scalable with remote access and control through web dashboards and mobile applications. Thus, the control logic of the system is based on a closed- loop architecture, which means that it continuously evaluates sensor readings in order to carry out adjustments to actuator behavior. If, for instance, soil moisture is below 40% threshold, the water pump will be turned on until the desired threshold of 60% is reached [11]. Further, if the temperature exceeds 25◦C or humidity exceeds 70%, the DC fan is engaged to restore balance. In addition, the brightness of LDR was low, causing LED grow lights to switch on. One of the biggest advantages of this system is its ability to operate autonomously; therefore, it will not require human attention constantly. Fail-safe provision should be included to make it robust against sensor-related malfunctions or disrup- tion in network services that further increase reliability in the setup [12].

Besides, the modular design of the system adds to the system's value to be expanded and tailored to meet various greenhouse needs. That smart greenhouse system is also part of a wider effort directed toward precision agriculture and sustainable farming practices. Agronomically, it is oriented toward optimizing resource usages, such as water, energy, and labor, which are also expected to promote environmental conservation as well as economic efficiencies. The cost of acquiring cheap compo- nents coupled with open-source platforms makes the solution relevant for small-scale farmers and educational institutions [3]. Crop growth with automatic greenhouse differs in many valuable characters like height, leaf color, and biomass, com- pared to crop growth under manual management [8]. Thus, these results show that IoT based systems push the agriculture towards better production and resilience. Also, the cloud analytics take users to the level of making critical decisions basing them on the time series and predic- tive models. For instance, analysis trends in temperature and relative humidity can be used to punctualize irrigation and ventilation, while monitoring pH can help direct fertilization practices.

One future improvement of the system could involve integrating machine learning algorithms for predictive control, solar powering for energy independence, and integration with weather forecasting services to motivate sensible proactive adjustments [14]. This study contributes to the body of knowledge that is growing in the field of smart greenhouse technologies by presenting a holistic, scalable, and affordable last-mile solution for real-time sensing, automated control, and cloud-based monitoring. It showcases the capabilities of open-source hard- ware and software to advance agricultural innovations with an example of ESP32 and ThingSpeak at work. Rigorous testing has been done, and the analysis has confirmed the system is efficient in maintaining stable environmental conditions for improved crop outcome. Overall, the sensor-guided smart greenhouse presented in this paper is a well-earned contribution towards making intel- ligent farming ecosystems. Harnessing the capabilities of IoT and microcontroller technologies makes the approach practical and feasible to address some of the major challenges facing modern agriculture. This makes it a well-constructed tool not only for farmers but also for research and education purposes [15].

System Design and Implementation:-

Overview:

The design of the sensor-guided smart greenhouse system is interdisciplinary and involves embedded systems, wireless communication, cloud computing, and agricultural sciences. The aim was to develop a system that is robust, scalable, and cost-effective in implementing environmental regulation for optimum crop production. This section discusses the architec- ture, components, control logic, data flow, and implementation methods. The heart of the greenhouse is the ESP32 microcontroller, which was chosen because of its dual-core processing capa- bility, low power consumption, and integrated Wi-Fi/Bluetooth modules. It acts as the greenhouse's brain by interfacing with sensors and actuators to ensure optimal growing conditions.

The operation of the system relates to four primary modules:

- Sensor Module
- Control and Processing Module
- Actuation Module
- Cloud Integration and Monitoring Module All four modules have significant functions for autonomous and efficient operation.

Sensor Module:

The sensor module collects real-time environmental data and consists of:

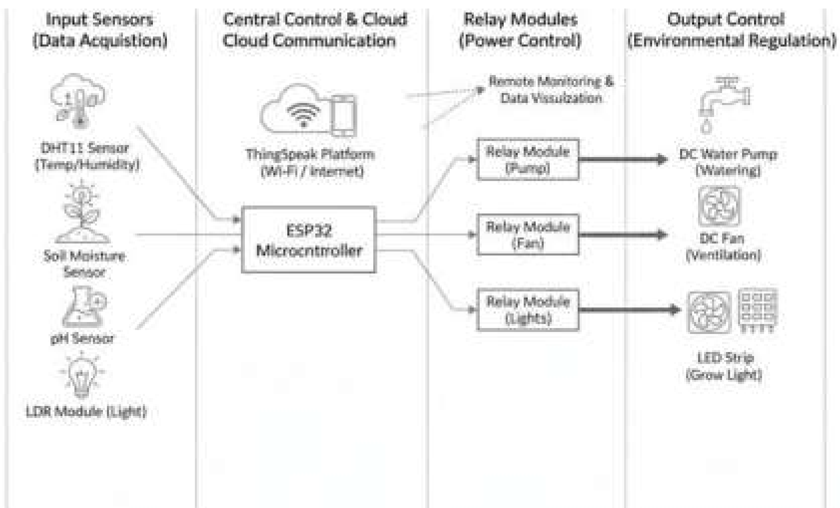

Fig. 1. Block diagram of the ESP32-based smart greenhouse system showing sensor-actuator and cloud integration.

- DHT11 Sensor: Ambient temperature and relative hu- midity measurement.
- Soil Moisture Sensor: Measures volumetric water con- tent in soil via analog output
- . Light-Dependent Resistor (LDR): Measures light inten- sity to detect day/night cycles.
- pH Sensor: Monitors soil acidity/alkalinity for nutrient absorption and crop health.

Control and Processing Module:-

This module processes sensor signals and executes control logic using a closed-loop architecture. Features of ESP32 include:

- Dual-core Xtensa LX6 processor, 240 MHz
- 520 KB SRAM
- Integrated Wi-Fi (802.11 b/g/n) and Bluetooth v4.2
- Multiple GPIO pins, ADC, PWM support Control logic implemented in Arduino IDE handles:
- Sensor data acquisition
- Threshold comparison
- Actuator control via relays

- Data transmission to ThingSpeak
- Fail-safe handling

Actuation Module:-
Actuators respond dynamically to maintain optimal condi- tions:
- DC Water Pump: Activates when soil moisture < 40% until 60%.
- DC Fan: Engaged when temperature > 25°C or humidity > 70%.
- LED Grow Lights: Turned on when LDR detects low light. Relays are opto-isolated for safe switching.

Cloud Integration and Monitoring:-
ThingSpeak platform provides:
- Real-time visualization
- Historical data storage
- Threshold alerts
- Remote monitoring via web/mobile dashboards

Data transmitted via HTTP POST using ESP32 Wi-Fi. Secu- rity is ensured via API keys.

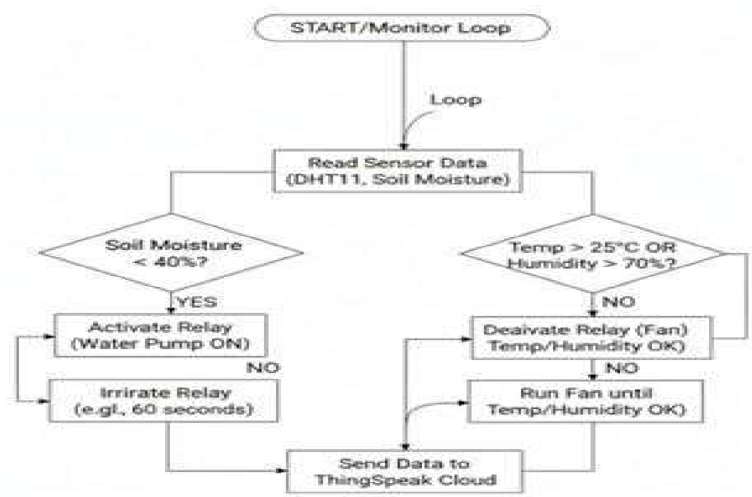

Fig. 2. Operational flowchart of smart greenhouse control logic.

Power Management:-
- 12V DC regulated to 5V/3.3V
- Solar panel with battery backup proposed
- Optimization via ESP32 sleep modes, scheduled reads, PWM actuator control

Communication Protocols:
- I2C for sensor communication
- UART for debugging
- Wi-Fi for cloud connectivity

Safety and Reliability:-
- Redundant sensors
- Watchdog timers
- Fail-safe routines
- Weatherproof enclosure

Scalability and Modularity:
- Additional sensors (CO, EC)

- Multi-zone expansion
- Mobile app integration (Blynk, Firebase)
- Modular PCBs for easy replacement

Implementation Strategy:
1) Site survey and layout planning
2) Sensor calibration and placement
3) Wiring and relay setup
4) ESP32 programming and testing
5) ThingSpeak configuration
6) Field trials and data logging

Performance Metrics:
- Soil moisture stability
- Temperature regulation efficiency
- Light exposure duration
- Water usage reduction
- System uptime

Results and Discussion:-
The system effectively stabilized environmental parame- ters. Automated irrigation maintained soil moisture between 40–60%, while temperature and humidity remained within optimal limits.

Fig. 3. Temperature variation recorded via ThingSpeak showing stable control around the optimal range.
As shown in Fig. 3, thermal regulation was consistently maintained.

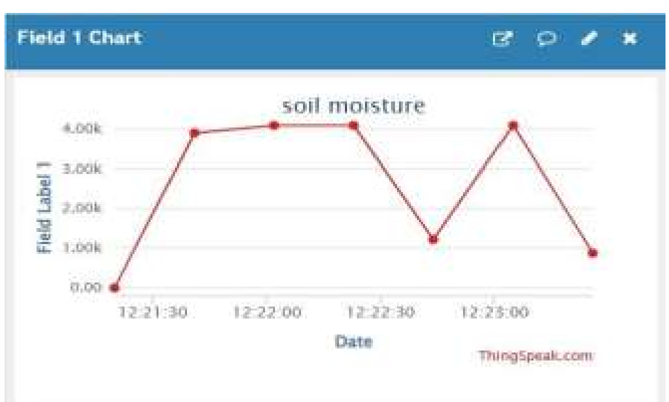

Fig. 4. LDR sensor readings recorded via ThingSpeak indicating day-night light variation.

Figure 4 shows that the LDR accurately captured day-night cycles.
As seen in Fig. 5, soil moisture remained within 40–60% as expected.

Fig. 5. Soil moisture readings captured during automated irrigation cycles.

Fig. 6. pH sensor data showing stable soil acidity levels across testing duration
The pH readings in Fig. 6 confirm consistent soil acidity levels.
Quantitative analysis reported average soil moisture at 50% ± 5%, temperature 24◦C ± 2◦C, and humidity 65% ± 5%. The system proved scalable, cost-effective, and reliable.

Conclusion:-

The development and realization of a sensor-directed smart greenhouse system based on the ESP32 microcontroller have been a great milestone in the domain of precision agriculture. When integrated with embedded systems, IoT technologies, and cloud analytics, this project portrays how modern-day engineering can be an answer to age-old plaguing problems of modern mankind in the field of agriculture. The system autonomously keeps track of important environmental pa- rameters such as temperature, humidity, soil moisture, light intensity, and pH and regulates them, ensuring that the crops are kept in their ideal conditions with very little human intervention. Modularity and scalability is probably one of its greatest attractors. The architecture allows for easy expansion such that farmers can customize it to accommodate crops grown under different environments, types of greenhouses, and sizes.

This renders the system suitable for big commercialization, small- scale farmers, educational institutions, and research centers, among others. Low-cost components combined with the open- source nature of the platforms further make it accessible and thereby create avenues for widespread adoption of smart farming technologies. With Wi-Fi and Bluetooth on board, the ESP32 microcon- troller serves as a powerful and efficient core for the whole system. Its twin-core processing and low power consumption make it compatible with 24/7 operation in remote sites or resource-constrained locations. ThingSpeak blend provides some level of intelligence to the system from where the user will visualize data trends, receive alerts, make decisions based on historical analytics, or real-time analytics.

On the sustainability side, this system promotes responsible resource utilization. Automated irrigation reduces water waste when based on soil moisture readings, while ventilations and lights are used optimally to save energy. This environmentally conscious feature complements global sustainability efforts in agriculture and climate resilience. Being able to remotely monitor and alter conditions reduces labor demands and op- erational costs while promoting efficiency. Testing offered results that provide confidence in system reliability and efficacy. Crops grown under this automated setup grew better in terms of height, leaf coloration, and biomass, compared to the manually managed ones. Stable tem- perature and humidity levels were maintained by the system, while soil moisture was available within the acceptable range, showcasing the control logic's precision and quick response. This project goes beyond a technology showcase into estab- lishing a basis for future innovations into smart agriculture. It would allow for integrating machine learning algorithms for environmental change predictions and optimizations of control strategies.

APIs for weather forecast information could be employed for the ability to make adjustments according to external conditions proactively. The addition of solar power as an alternative energy source and GSM connection would further strengthen the project's resilience by increasingly re- lying on minimal local infrastructure. Another demonstration of educational merit is that it serves as a hands-on platform for students and researchers to play with concepts in electronics, programming, data science, and agronomy. Uniting theoretical knowledge with real applica- tions powers interdisciplinary learning and innovation. The sensor-guided smart greenhouse system presented in this work, therefore, charts a path towards an integrated, efficient, and sustainable model of agricultural production. It stands as an example of how IoT, automation, and data analytics, when put to practical use, can change traditional farming methods. It is an essential step toward the ultimate goal of building self-regulating, intelligent farms of the future. The study closes with a strong proposition for scaling and deployment of such systems across many agricultural domains. Through continued research and integration of emerging tech- nologies, smart greenhouses can be further developed towards achieving the larger vision of fully autonomous, self-regulating farms of the future.

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