Automated Smart Greenhouse System Using Iot

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***Abstract*—The growing demand for sustainable agricultural production is driving many farmers to implement automated technologies. This paper presents the design and implementation of a smart greenhouse using an IoT platform based on an ESP32 module. This system uses sensors to monitor the four main environmental parameters temperature, humidity, soil moisture, and light intensity in real-time. When these parameters reach defined thresholds values, control devices such as irrigation pump, ventilation fan, and artificial lights are controlled automatically by the ESP32 microcontroller to maintain optimal conditions for plant growth. The system allows data transmitted in real-time to a cloud-based dashboard through Wi-Fi, thus allowing for monitoring and overseeing the system remotely. The method of automation is hardware-based and threshold-based, both of which provide lower computational complexity and energy efficiency. Experimental evaluation has shown the system to successfully provide reliable environmental conditions, reduced water consumption, and stable wireless communications. The prototype developed provides a cost-effective way to implement a solution that is scalable to small and medium-sized greenhouse applications, which will help to achieve sustainable and intelligent agricultural automation. The proposed hardware-focused solution offers a low-cost, energy-efficient, and scalable approach for sustainable greenhouse automation, making it suitable for small- and medium-scale agricultural applications.**

I. INTRODUCTION

Agriculture is an essential component of global food security and financial stability. However, the agriculture industry is threatened by population growth, changes in climate, lack of water resources, and unpredictable environmental conditions, all of which present challenges to sustainable agricultural production. Traditional agricultural practices are commonly based on manual monitoring and control of environmental variables; this often results in the inefficient use of resources, decreased crop yield, and increased operating costs. Greenhouses have become increasingly valuable tool for protecting crops from damaged caused by changes in weather and to allow farming procedures to be controlled. Greenhouses create an ideal microclimate for plant growth by controlling the temperature, humidity, soil moisture content, and light reached by plants that grow in that microclimate.

However, to achieve these are not be done without a high level of human management. The current management systems require individuals to constantly check on plants and make any required adjustments manually, making it difficult to scale up operations and increase efficiency. The most recent developments in IoT have allowed for the design of smart agricultural management systems that allow people to monitor their crops in real time, as well as control the environment around their crops using automated processes. Smart greenhouse systems use various types of sensors and microcontrollers, along with wireless communications to collect and relay real time data about the environment to users for the purpose of controlling and regulating the operation of greenhouse systems. This approach also leads to improvements in resource usage, reduction of water usage, and better crop growing environments. There are many different platforms for connecting devices that are part of the Internet of Things (IoT), but one microcontroller, The Espressif ESP32 (ESP32), has garnered a lot of interest lately because of its low-cost, low-power operation, built-in Wi-Fi support, and enough processing capabilities to run real-time embedded applications with ease. An automated greenhouse can be controlled by implementing a threshold-based automation control method without the use of complicated calculations and control algorithms, reducing the complexity of the system and conserving energy [1].

This paper proposes and implements an IoT-based automated smart greenhouse system using the ESP32.

The system will monitor multiple environmental parameters such as temperature, humidity, soil moisture content, and light intensity - individually and as a group. Automated control actions will be initiated based on pre-set threshold values to keep the crop in the best possible growing environment. Management and monitoring will be performed remotely using a cloud-based dashboard by transmitting real-time data from the ESP32 to the cloud. The paper provides a cost-effective, energy-efficient, and scalable alternative for sustainable greenhouse automation applications mostly targeted toward small- and medium-size commercial agriculture production facilities.

1. Need for Sustainable Agriculture

As the population continues to rise rapidly, it is essential that we develop sustainable agricultural practices that conserve and protect the environment while continuing to provide food for our growing population [2]. There are many different types of sustainable agricultural practices that can help farmers use the earth's resources more effectively, including soil, water, and biodiversity, ensuring long-term food security and ecological balance [2]. The current global population is putting enormous strain on agricultural systems to produce larger quantities of food while maintaining environmental sustainability [2].

High levels of chemical fertilizer and pesticide usage are major concerns that highlight the urgent need for sustainable agriculture [3]. Soil degradation, water pollution (both surface and groundwater), and biodiversity loss caused by excessive agrochemical consumption emphasize the importance of adopting environmentally responsible farming methods [3]. Examples of sustainable agricultural practices include crop rotation, conservation tillage, and efficient irrigation techniques, which help improve soil quality and optimize water resource utilization [3].

Research studies indicate that sustainable agriculture not only reduces greenhouse gas emissions but also enhances farmers' resilience to climate change impacts such as prolonged droughts, extreme temperatures, and irregular rainfall patterns [4]. Furthermore, sustainable farming systems have been shown to improve farm profitability while ensuring long-term environmental protection and food security for future generations [2].

2. IoT in Farming

Smart Agriculture is also known as IoT (Internet of Things) and consists of Integrated Systems that are built using various technical elements including Sensors, Communication Networks, and Cloud Computing to create applications in the form of databases. The primary function of the Sensors is to monitor several environmental conditions (including moisture level in the soil, temperature of the soil, humidity in the air, and light levels in the air) and relay this information to a Cloud-Bases System that provides analytics for controlling irrigation, fertilization and pest control [5]. The greatest benefit that IoT systems provide to agriculture is precision agriculture, where Inputs (such as Irrigation and Fertilization) are only applied when they are needed; thus, reducing waste, and decreasing the impact on the environment (to enhance the sustainability of Agricultural Production Systems) [6]. The also give producers the ability for real-time, remote Monitoring (through Mobile Devices and Dashboards), which help producers detect problems before they become an issue in their production, and help make timely decisions regarding production. In addition, Producers have historical records that they can use to run Predictive Analyses to estimate Crop Yields and identify potential issues to their crops (caused by disease) [6].

II. RELATED WORK

2.1. Existing Greenhouse Monitoring Systems

Control systems are available in many forms to increase crop yield, and provide an improved growing environment, using environmental sensors and control devices [7]. Early systems utilized wired sensors for the control of one or more basic parameters such as relative humidity, temperature and local control devices; however; they did not have remote access and did not provide any sort of real-time information regarding the data being collected. With the introduction of wireless sensor networks (WSN), the deployment of distributed greenhouse monitoring systems began to develop, so that soil moisture, light levels and CO_2 levels could be measured over greater distances. Because distributed monitoring systems reduce field-wiring complexity, they have improved dramatically [8]. Presently, there are systems based on the Internet of Things (IoT) that have connected sensors to cloud computers through the Internet. This allows users to remotely access fitted resource management (irrigation, ventilation, and lighting) from mobile apps or web-based dashboards with real time data coming directly from the sensors to the cloud through the Internet [9]. Automated control of irrigation, ventilation, and lighting (by utilizing proper sensor feedback) has also been built into the state-of-the-art greenhouse monitoring systems [7]. While state-of-the-art greenhouse monitoring systems have increased the efficiency at which the user can manage the greenhouse, they have also allowed for a greater opportunity for developing botanic gardens and nursery stock (i.e., from seed to sale) by making it feasible to utilize multiple sensors and sources of data to aid in the development of various stages of growth from seed to mature plants. Limitations.

Although greenhouse automation and IoT-based monitoring systems provide significant benefits, they face limitations related to cost and technical complexity [9]. The initial investment required for sensors, microcontrollers, communication modules, and automated control systems can be high, particularly for small-scale farmers. Advanced components such as CO_2 sensors and cloud-based platforms further increase implementation costs [10].

System complexity is another major challenge. The integration of multiple sensors, wireless communication protocols, and cloud services requires technical expertise for installation and maintenance [11]. Additionally, IoT systems depend on reliable internet connectivity and stable power supply, which may not be consistently available in rural areas [10]. Scalability also increases configuration and data management complexity [9]. Therefore, despite their advantages, cost and technical challenges remain key barriers to the widespread adoption of greenhouse automation systems.

2.2. System Architecture

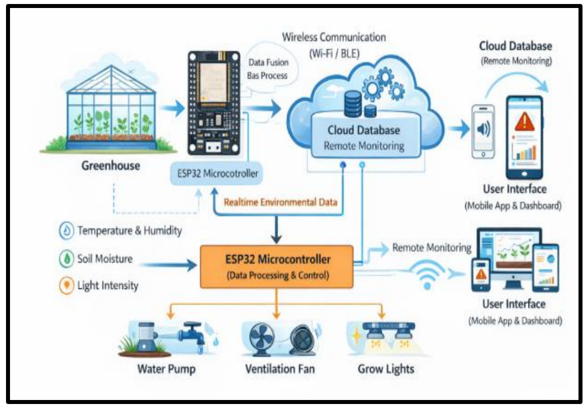

Fig. 1. IoT-Based Smart Greenhouse System Architecture

A. Hardware components

The embedded control system uses an ESP32 microcontroller board to provide the electrical interface for the control system and the sensors. [12]. The ESP32 has numerous applications in IoT because of its built-in Bluetooth and Wi-Fi connections, impressive processing abilities, and extensive number of peripheral interface options available [12]. The ESP32 is very well suited for use in smart agriculture and greenhouse automation systems because it can monitor sensors in real-time and send that data wirelessly. [12].

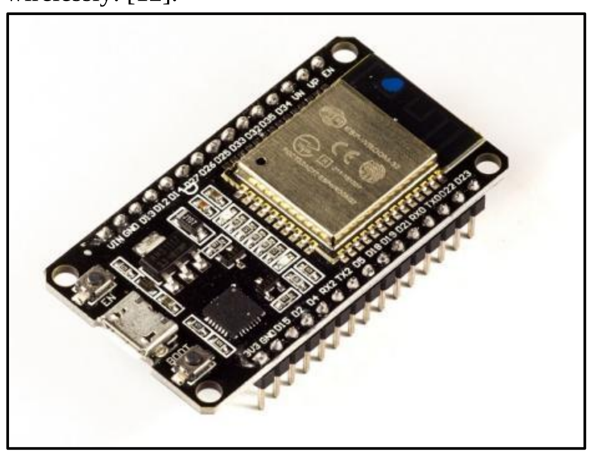

Fig.2 ESP 32

B. Temperature and Humidity Sensor (DHT22)

The DHT22 temperature and humidity sensor is used in many IoT Applications such as environmental monitoring and smart agriculture due to its low cost and stability [13]. The DHT22 combines two different sensing technologies (capacitive humidity and thermistor) in one device to provide accurate relative humidity and ambient temperature readings. The

DHT22 converts the sensors' analog output onto calibrated digital output within the sensor; then it transmits this measured data back to the microcontroller (such as ESP32) using a single wire protocol. The DHT22 can measure temperature from -40 degrees to 80 degrees Celsius with an accuracy of +/- 0.5 degrees Celsius. The DHT22 can also measure relative humidity from 0 to 100% with an accuracy of +/- 2-5% [13]. Additionally, the DHT22 operates between 3.3V to 5V, making it compatible with microcontrollers like the ESP32. The DHT22 operates on an approximate 2-second sampling period; this sampling frequency is appropriate for environmental monitoring. In smart greenhouse applications, the DHT22 periodically measures and sends back information about environmental conditions to the ESP32, which will activate other control devices like fans, HVAC, etc., based on predefined conditions. The DHT22 is a good candidate for small- to medium-size greenhouse automation systems because it has a wide measurement range, good accuracy, low power consumption, and a simple digital interface.

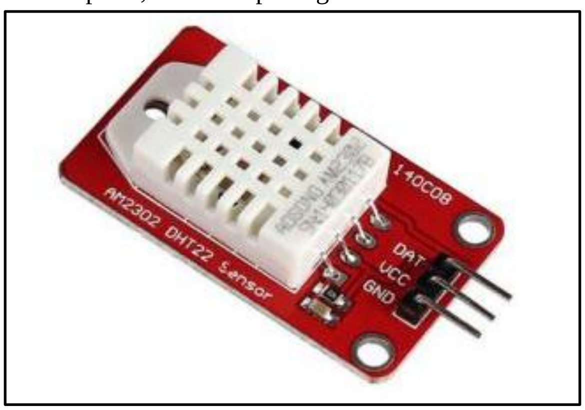

Fig.3 DHT22

C. Soil Moisture Sensor

Soil moisture sensors assist smart greenhouse agriculture (and precision agriculture) by allowing for measurement of the volumetric water content of soil [14]. This is essential to monitor the environmental conditions in order to provide the appropriate irrigation to grow healthy plants. Capacitive sensors have the highest reliability in terms of the durability and corrosion resistance of the sensors, and are therefore best suited to measure soil moisture content [14]. The analog voltage produced by a capacitive sensor can be conditioned and converted to a digital signal via an ADC (analog to digital converter) on an integrated ESP32 microcontroller. The proposed system can compare the data from the sensor(s) with continuously measured thresholds of irrigation. If the level of moisture at the sensor(s) is below the corresponding threshold, the irrigation pump will be automatically activated via a relay [15]. Automatic irrigation will reduce water wastage through improper use, increase irrigation efficiency and contribute to the sustainable development of agriculture. Soil moisture sensors are also an excellent choice for small to medium sized operations to automate their operations in their greenhouse, due to their low cost and ease of use.

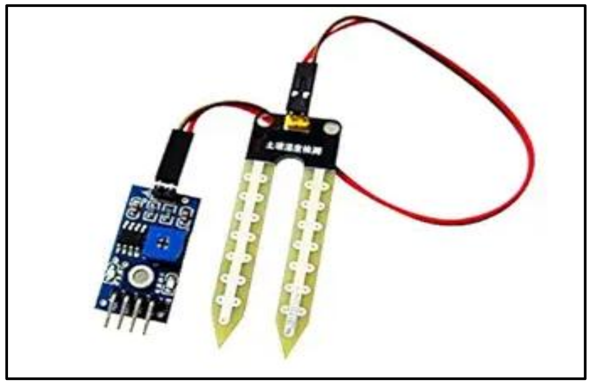

Fig.4 soil moisture sensors

D. Communication Structure

The system for smart greenhouses based on IoT offers a communication system that provides real-time transmission of data and allows remote monitoring through wireless connections [16]. Environmental parameters such as temperature, humidity, soil moisture, and light intensity are measured by sensors; this data is sent to an ESP32 microcontroller, where it is processed. The ESP32 microcontroller reads sensor data sent from hardware and compares it against a pre-set threshold value before controlling actuators. The ESP32 sends collected data using its built-in Wi-Fi module to a cloud server via either HTTP or MQTT protocols for remote monitoring and storage of the greenhouse’s data. This wireless communication design enables reliable, scalable, and affordable automation of greenhouses.

III. METHODOLOGY

A. Sensor Data Acquisition

A smart greenhouse system first requires sensor data collection, which collects sensor data from environmental factors collected from multiple sensors [17]. The DHT22 sensors measure temperature and humidity while the soil moisture sensor measures soil moisture content and the light sensor measures light intensity. These sensors send data to the ESP32 microcontroller in real-time through digital and analog interfaces. Once data is obtained, data can either be processed for comparison with predetermined value limits; this allows the greenhouse to be maintained efficiently as well as accurately with a continuous sensor system.

B. Threshold-Based Automation

Smart greenhouse has been developed to use threshold-based automated control systems to manage the ideal climate for plants (e.g., temperature, humidity, etc.) by using an ESP32 microcontroller to monitor various types of sensors (such as soil moisture, humidity, and airflow) that generate data continuously. By comparing this sensor data to predefined threshold values for each parameter, the controller will activate the actuators (such as irrigation pumps, exhaust fans, and grow lights) to provide optimal conditions. This process reduces the number of times the controller must perform calculations and, therefore, the energy consumed by the controller, while providing highly accurate and timely control of greenhouse operations [18].

C. Control Logic

To develop a smart greenhouse system, the decision-making logic is implemented by the ESP32 Microcontroller [19]. The microcontroller uses real-time sensor data with predetermined conditional logic to provide automatic operation of the environmental systems. Control signals to actuators (such as irrigation pumps, ventilators or lights) are generated by comparing sensor measurements to threshold values and informing the appropriate component to operate. This type of control strategy (rule-based) provides stable environmental conditions, reduces computational complexity, and allows the greenhouse system to function in an energy-efficient manner.

D. Wireless Transmission

The ESP32 microcontroller in a smart greenhouse uses its built-in wireless capabilities to communicate data collected by different devices and transmit the data to many different controllers. Data that is received by the application may be collected through HTTP or MQTT (or both) depending on the database that exists on the ESP32 microcontroller in order to store this information. All of this is possible because the analysis of historical event records and monitoring of current data can be done from a cloud software-based server to allow for a seamless operation of the smart greenhouse without risking connections to other devices. This ultimately provides for the efficient management of your greenhouse system simply through the use of the built-in wireless capabilities of the ESP32 microcontroller. [20]

IV. EXPERIMENTAL RESULTS

A. Temperature Stabilization

The testing of the smart greenhouse's performance has demonstrated that the smart greenhouse system holds temperature restrictions to a specific range through the use of an ESP32 microcontroller to control a ventilation fan if the temperature exceeds the upper threshold. The ESP32 microcontroller will also control various other devices to ensure that when the temperature is below its designated threshold range, actions are taken accordingly. The DHT22 sensor, which continuously monitors the indoor environment, is capable of supplying precise real-time temperature readings to the system. Overall, the developed automation mechanism will serve to reduce temperature fluctuations, create a healthy atmosphere for plant development, and minimize the amount of energy that is wasted on unnecessary heating or cooling of the greenhouse. [19]

B. Water Saving Estimation

The smart greenhouse system's experimental evaluations have indicated that it provided an increase in water savings, which have been attributed to the automation of irrigation. The purpose of this system is to allow the irrigation pump to only operate when the moisture content of the soil drops below a predetermined threshold level so that no irrigation occurs during periods of adequate moisture. By continuously monitoring the moisture content of the soil, the system provides plants with what they need to survive (and potentially thrive) as required on an ongoing basis. When considering the traditional means of manually irrigating crops, an automated irrigation system will provide optimised water use and consequently reduce water wastage, as well as demonstrate examples of efficient management of water resources for respect for the environment and conserving resources.

C. System Response Time

To determine when the system is responding, we needed to analyze the time taken from when the sensor data is received and processed by the controller to when the required actuators are triggered to operate according to that processed data. The results showed that the ESP32 microcontroller is very fast at processing sensor data and creating control signals, which will allow actuators (i.e., irrigation pump or ventilation fan) to be activated almost as soon as any environmental parameter crosses a defined threshold limit. The short response time indicates that real time control can be maintained for environmental factors and that stable greenhouse conditions can be achieved. Therefore, the experimental results indicate that the proposed system can provide an efficient automated control solution in a timely manner, and will function successfully within a smart agronomy application.

V. CONCLUSION

This study aims to investigate how an Internet of Things (IoT) automatic system can use the ESP32 Microcontroller to create a sustainable agricultural practice through the development of a smart greenhouse. The smart greenhouse has an automation system embedded within, which includes multiple sensors that continuously monitor critical environmental variables such as temperature, humidity, soil moisture and light levels in real time. The results from the experiments indicate that the automation system stabilizes temperature levels in the environment, reduces water required to grow plants and minimizes time taken by the system to respond to changes in the environment. The automated irrigation system utilizes a threshold-based control system to supply water to the crop's root system when soil moisture levels fall below a certain threshold to prevent excess soil wetting or water resource wastage. The automated control system was able to wirelessly transmit real-time data through the ESP32's built-in Wi-Fi module, which provides a means of remote monitoring and controlling greenhouse operations through the cloud

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