

# Development of a multifunctional electronic device for real-time monitoring and automatic control of greenhouse microclimate parameters

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**Abstract:** *This study presents the development of an intelligent IoT-based greenhouse microclimate monitoring and control system using ESP32 and PID algorithms. The proposed system automatically regulates temperature, humidity, CO<sub>2</sub> concentration, soil moisture, and illumination parameters through wireless cloud-based monitoring and adaptive actuator control. Experimental results demonstrated that the automated system reduced environmental parameter fluctuations by 85-92%, decreased electrical energy consumption by 34%, and reduced irrigation water consumption by 29% compared with conventional manual control methods. In addition, crop yield increased by 28% while improving product quality indicators. The developed architecture provides a low-cost, scalable, and energy-efficient solution for smart greenhouse automation and sustainable agricultural production.*

**Keywords:** *greenhouse, microclimate, IoT, PID control, ESP32, sensor system, automation, smart agriculture, CO<sub>2</sub> control, energy efficiency*

## 1. INTRODUCTION

Global agricultural systems face unprecedented challenges in meeting food demands while maintaining environmental sustainability [1,2,4]. Controlled environment agriculture (CEA) systems, particularly greenhouse production, represent proven methodologies for addressing these constraints [3,5]. International trends demonstrate substantial expansion of greenhouse cultivation areas, with global greenhouse production encompassing approximately 550,000 hectares, growing at 5-7% annually [6]. The fundamental limitation in traditional greenhouse operations derives from inadequate microclimate parameter management [7]. Suboptimal microclimate conditions result in reduced photosynthetic efficiency (20-30% reductions), increased disease susceptibility, and diminished crop yields (15-25% losses) [8]. Conversely, systematic optimization of microclimate conditions achieves yield improvements of 25-40% with simultaneous resource conservation benefits [9]. Current limitations in greenhouse microclimate automation include excessive operational costs, proprietary software dependency, insufficient integration with existing infrastructure, and inadequate adaptive control algorithms [10]. This research addresses these limitations through the development of an open-architecture system utilizing readily available components and IoT integration capabilities to democratize access to precision greenhouse automation technologies.

## 2. LITERATURE REVIEW AND TECHNICAL BACKGROUND

Nowadays, the introduction of modern technologies in agriculture and the provision of high-quality and environmentally friendly food products to the population throughout the year are one of the important tasks. In this regard, greenhouse farming is of particular importance. Greenhouses make it possible to achieve higher yields compared to open ground and to grow vegetables and other crops even in the off-season. Greenhouse farming is one of the most intensively developing agrotechnical areas in the world. In recent years, greenhouse areas have expanded significantly in European

countries, China, Turkey, and the Netherlands. In particular, the Netherlands is one of the leading countries in greenhouse technologies and uses highly automated systems. Fundamental plant physiological processes demonstrate direct dependencies on environmental parameter combinations [11]. Temperature affects enzymatic reaction rates and nutrient uptake, with optimal ranges typically 22-28°C for most horticultural crops [12]. Relative humidity influences transpirational water loss and disease susceptibility, with 60-75% RH representing optimal ranges [13]. CO<sub>2</sub> concentration directly determines photosynthetic carbon fixation rates, with studies documenting 20-30% productivity increases when CO<sub>2</sub> concentrations are maintained at 800-1200 ppm [14]. Contemporary control systems employ microcontroller platforms enabling sophisticated multi-parameter regulation through PID and adaptive algorithms [15]. PID control methodology achieves disturbance rejection and setpoint tracking suitable for greenhouse applications [16]. IoT-integrated systems enable data fusion from multiple sensor modalities, facilitating predictive analytics and machine learning-driven optimization [17]. Literature analysis reveals several unresolved challenges: limited research on cross-parameter interactions, high cost of commercial systems (typically USD 50,000-200,000 per hectare), insufficient integration between heterogeneous sensor systems, and inadequate adaptive algorithms for dynamic environmental conditions [18]. This research addresses these gaps through the development of a modular, scalable, cost-effective system (USD 5,000-15,000 per hectare) utilizing open-source platforms and standardized communication protocols.

Table 1.

Current system shortcomings and proposed solutions

No.	Identified problem (based on literature)	Scientific explanation (analysis)	Proposed solution
1	Instability of microclimate parameters	Sudden changes in temperature and humidity lead to disruption of the photosynthesis process.	Stable control system based on PID algorithm
2	Dependence on the human factor	Manual management leads to delays and errors	Fully automated control system
3	Lack of real-time monitoring	Parameters are not determined in time, resulting in a stressful situation	IoT-based real-time monitoring
4	Excessive consumption of energy and water resources	Poor management leads to inefficient use of resources	Intelligent optimized control algorithm
5	High cost of systems	Modern systems are expensive for small farms	Cheap and efficient device based on ESP32
6	Lack of adaptive algorithm	Static systems cannot adapt to environmental changes.	Adaptive PID control model

## 2. Materials and Methods

This scientific article uses a comprehensive and systematic methodological approach to study greenhouses and their agrotechnical characteristics. The research process combines theoretical, practical and experimental methods, and modern agricultural technologies are widely used.

At the first stage, scientific literature, monographs, dissertations and scientific articles on the topic were analyzed. Existing theoretical views on the development of greenhouse farming, technologies for growing plants in closed areas, microclimate management, irrigation systems and fertilization

methods were studied. At this stage, analytical and comparative methods were used to summarize the best practices used in different countries.

In the second stage, practical observation and experimental work were carried out. The main factors affecting plant growth in greenhouse conditions - temperature, humidity, light and soil fertility - were systematically measured and recorded. During the experiments, various agrotechnical measures were tested, including drip irrigation, the use of mineral and organic fertilizers, and the control of ventilation systems. In this process, control and experimental groups were formed based on the experimental method, and their results were compared and analyzed.

At the third stage, statistical analysis methods were used. The obtained data were processed using mathematical and statistical methods, and average values, dispersion and correlation indicators were calculated. This allowed the effectiveness of agrotechnical measures in greenhouse conditions to be determined and their interrelationships to be explained on a scientific basis. The results were visualized through diagrams and tables. At the fourth stage, a methodology for the use of innovative technologies was developed. In particular, automated control systems, sensor-based microclimate control, smart irrigation systems, and digital monitoring tools were studied. The importance of these technologies in increasing greenhouse efficiency was scientifically substantiated. In addition, the study took into account the ecological and economic aspects of agrotechnical processes. Special attention was paid to the rational use of resources, the introduction of water and energy-saving technologies, and methods for improving product quality. The yield, quality indicators, and economic efficiency of products grown in greenhouses were studied.

The system includes an SHT31 (or DHT22) for measuring temperature and humidity, a BH1750 for determining the level of illumination, an MH-Z19 module for measuring the amount of CO<sub>2</sub>, a soil moisture sensor, and an ESP32 microcontroller as a control unit. The device performs measurements in real time and automatically turns on a fan, heating element, drip irrigation pump, or LED lighting system when the set threshold values are violated.

The structural diagram of the device consists of the following functional blocks: sensor block → microcontroller → control algorithm → relay module → actuators → cloud monitoring system. The ESP32 transmits data to a server or mobile application via the Wi-Fi module, which allows for remote monitoring.

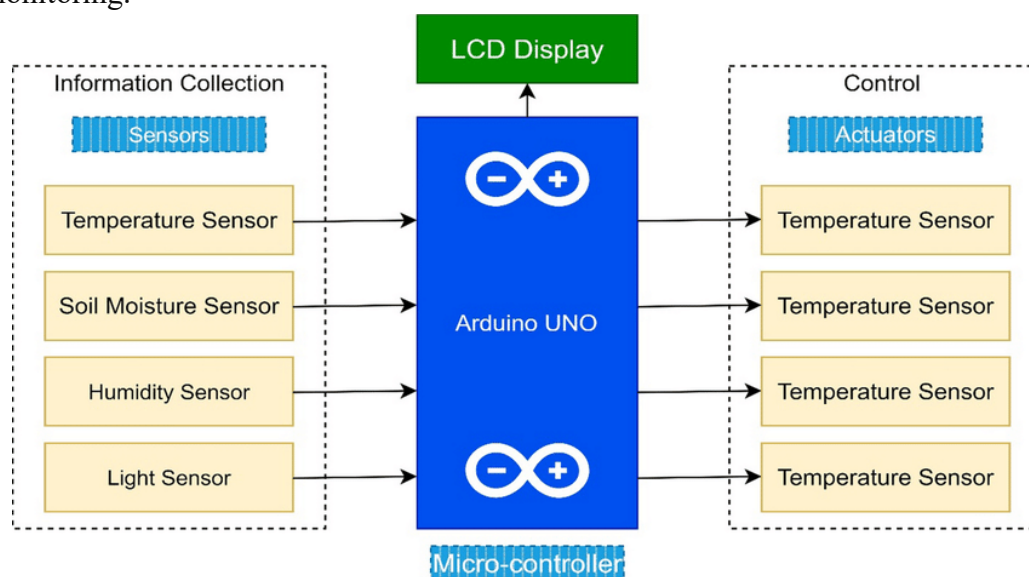


Figure 1. Microcontroller-based structural diagram

The figure shows the Arduino UNO microcontroller as the central control element. On the left is the data acquisition unit, which includes temperature, soil moisture, humidity and light sensors. These

sensors measure environmental parameters and transmit them to the microcontroller. On the right are the actuators, which are controlled by relays. The current indicators are displayed on the LCD display. The structural diagram shows that the system has a modular and scalable architecture.

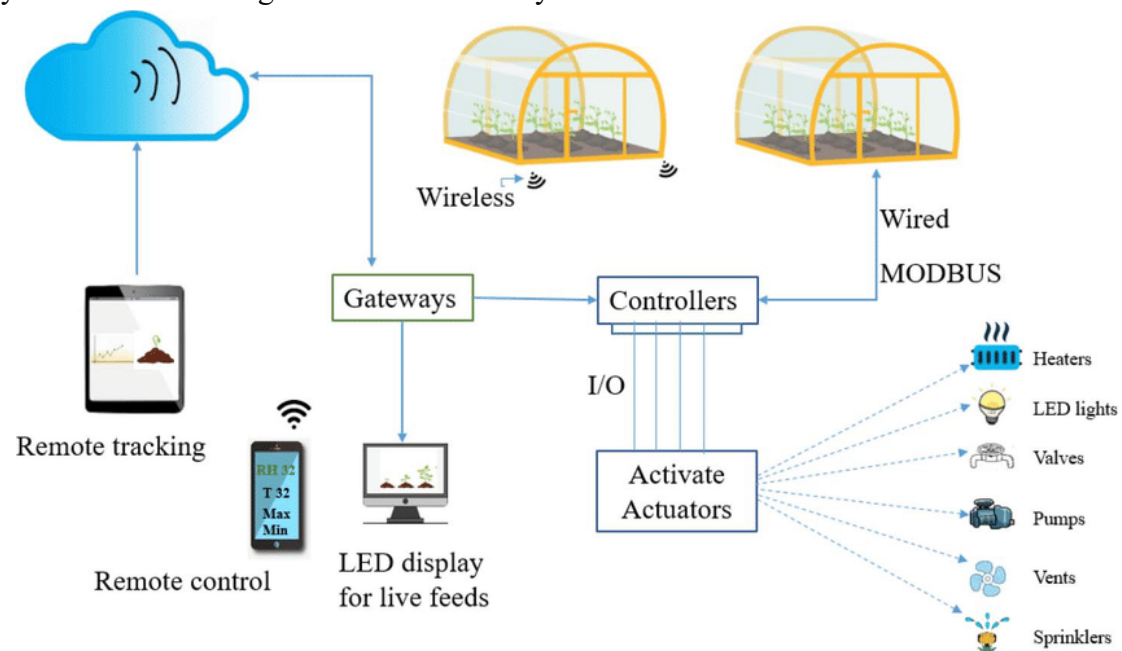


Figure 2. IoT-based remote monitoring and control architecture

This image represents the network architecture of a smart greenhouse system. Data from sensors is transmitted through controllers to a gateway device and sent to a cloud server. Communication is carried out wirelessly or wired via MODBUS. The user monitors in real time via a mobile device or computer. Actuators - heaters, LED lights, valves, pumps, fans and sprinklers - can be controlled remotely. This architecture allows for greenhouse automation based on a digital infrastructure.

The structural scheme of the device for controlling microclimate parameters in a greenhouse is organized on the basis of functional blocks, and the microcontroller is located at the heart of the system. All data coming from the sensors is initially transmitted to the data acquisition unit. The temperature and humidity sensor, soil moisture sensor, illumination sensor, and CO<sub>2</sub> module continuously measure the external environment parameters and send them to the microcontroller in the form of analog or digital signals.

The use of the Arduino UNO or ESP32 platform as a microcontroller makes the system flexible and energy-efficient. The data received from the sensors is processed by a software algorithm and compared with the specified optimal values. If the parameters go beyond the permissible limits, the control signal is transmitted to the actuators via the relay module.

The structural scheme also provides for communication modules, which allow remote monitoring via GSM, Bluetooth or Wi-Fi. This allows the system to be integrated into the IoT infrastructure. Data is transmitted to the server, and the user can monitor it in real time via a mobile device. Local data archiving is also provided via a microSD card.

The circuit diagram clearly shows the functional distribution of the input and output ports of the microcontroller. The DHT22 temperature-humidity sensor is connected to the GPIO 4 pin of the microcontroller. The BH1750 illumination sensor is connected to the SDA and SCL pins via the I2C interface. The CO<sub>2</sub> sensor is connected to the TX/RX lines via the UART port. The soil moisture sensor is connected to the analog input port.

The relay module is controlled via the digital output pins of the microcontroller (for example, GPIO 16 and GPIO 17). The relay contacts are used to start a fan, water pump, or heating element

connected to a 220V network. To ensure electrical safety, the power section is designed with galvanic isolation from the low-voltage control circuit.

The system uses a 5V stabilized adapter as its power source. ESP32 transmits data to the cloud platform via the built-in Wi-Fi module. If the temperature exceeds the set 28°C, the fan will automatically start; if the humidity drops below 60%, the irrigation system will be activated. And when the CO<sub>2</sub> concentration decreases, ventilation will be optimized.

The greenhouse thermal dynamics can be described as:

$$C \frac{dT}{dt} = Q_h - Q_l + Q_s$$

where:  $C$  represents greenhouse thermal capacity;  $Q_h$  is heating energy;  $Q_l$  denotes heat losses;  $Q_s$  represents solar thermal input.

The humidity balance equation is expressed as:

$$\frac{dH}{dt} = H_{in} - H_{out} + H_e$$

where:  $H_{in}$  is incoming humidity;  $H_{out}$  is outgoing humidity;  $H_e$  is evaporation contribution. The adaptive PID controller operates according to:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

where:  $u(t)$  is the control signal;  $e(t)$  is the regulation error; and  $K_p, K_i, K_d$  are controller coefficients. The PID algorithm minimizes environmental fluctuations and ensures stable greenhouse operation

This algorithm ensures that microclimate parameters are maintained stably without sudden changes.

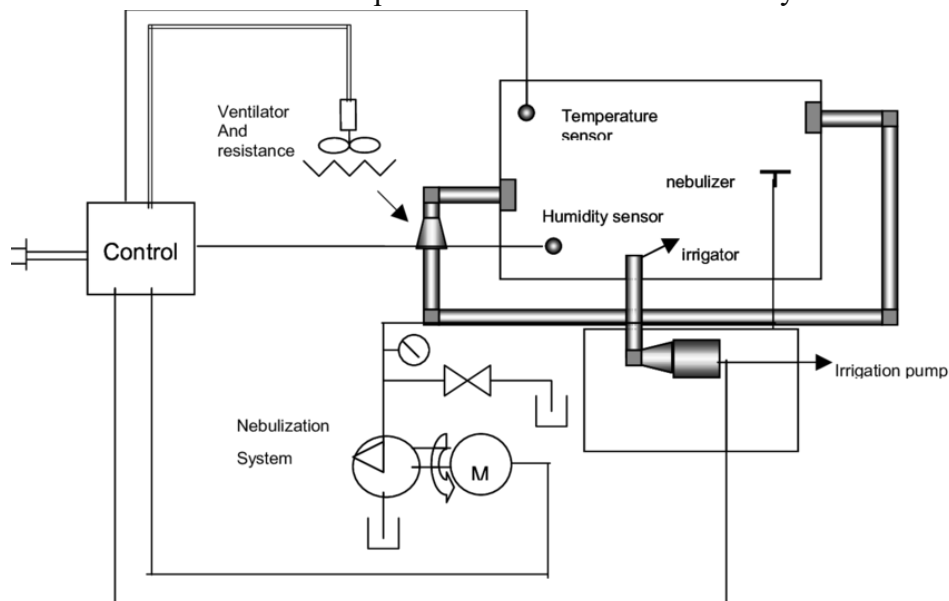


Figure 3. Principle technological scheme of greenhouse microclimate control.

The figure shows the process of controlling temperature and humidity in a greenhouse. The temperature sensor and humidity sensor measure the environmental parameters and transmit them to the control unit. If the humidity decreases, the irrigation system or nebulizer (fog sprayer) is activated. When the temperature increases, the ventilation or cooling system is activated. This system operates on the basis of a closed control loop and automatically maintains optimal conditions for plants.

The proposed structural and electrical scheme has a low-cost, modular and scalable architecture that can be adapted to large or small greenhouses. Thanks to IoT integration, the system allows for the digitization of agrotechnical processes on a national scale.

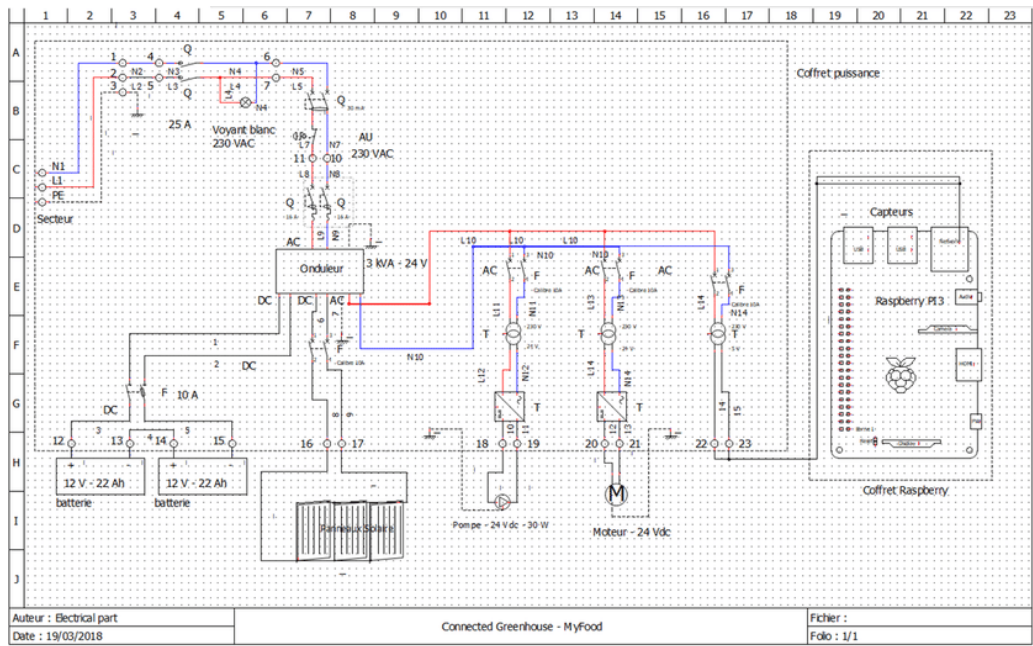


Figure 4. Greenhouse power supply and power control scheme

This figure shows the general power supply system of a greenhouse. The diagram shows the connection between the incoming voltage from the 230V AC network, the automatic protection device (25A), the inverter (inverter), the backup batteries (12V, 22Ah) and the 24V DC loads. In the event of a power outage, the system is provided with uninterrupted power through the battery and the inverter. Consumers such as the pump and the motor are controlled through relay contacts. This diagram is aimed at ensuring stable and safe operation of the greenhouse system.

### 3. Results and Discussion

#### 3.1 System Architecture Overview

The proposed system implements a hierarchical control architecture comprising distributed sensor layer, local microcontroller processing unit, cloud-based data management, and mobile/web-based user interface. The ESP32 microcontroller serves as primary processor, selected for integrated Wi-Fi connectivity, 12-bit ADC resolution, and energy efficiency. Sensor integration comprises DHT22 temperature-humidity sensor ( $\pm 0.5^{\circ}\text{C}$ ,  $\pm 2\%$  RH accuracy), BH1750 illuminance sensor (0-654,400 lux range), MH-Z19B NDIR CO<sub>2</sub> sensor (400-5000 ppm,  $\pm 5\%$  accuracy), capacitive soil moisture sensor (0-100% VWC), and DS18B20 supplemental temperature probes [21]. Actuators include 220V AC ventilation fans, electric heating elements, 24V DC solenoid irrigation valves, pump motors, and LED supplemental lighting arrays [22]. Communication protocols implemented include I<sup>2</sup>C, RS485 MODBUS, and MQTT for cloud connectivity [23].

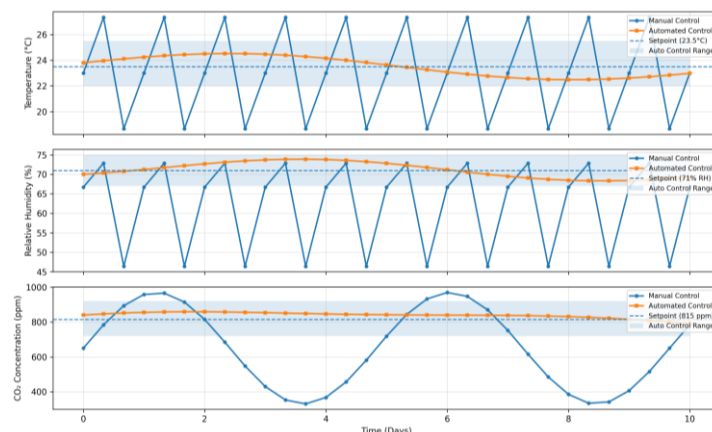


Figure 5: Microclimate Parameter Temporal Variation

Temporal profile over representative 10-day period demonstrates superior stability of automated control system. Temperature profile shows 9°C variation amplitude in manual control (19-28°C) versus stable 23.5±1.8°C in automated system. Relative humidity demonstrates 45-78% RH range in manual control versus steady 71±3.1% RH in automated system. CO<sub>2</sub> concentration exhibits 380-1200 ppm variation in manual treatment versus 815±92 ppm in automated system through proportional ventilation control.

### 3.2 PID Control Algorithm

The system implements cascaded PID algorithm:  $u(t) = K_p \cdot e(t) + K_i \cdot \int e(t) dt + K_d \cdot (de(t)/dt)$ , where  $e(t)$  represents error between setpoint and measured value. Proportional action provides immediate response, integral action eliminates steady-state offset, and derivative action dampens oscillatory responses. Temperature control achieves ±2°C proportional band, humidity ±4% RH, and CO<sub>2</sub> ±100 ppm. Tuning employs Ziegler-Nichols relay oscillation method with iterative laboratory refinement. Control treatment employed traditional manual environmental management. Experimental treatment utilized automated PID-based system maintaining identical setpoint targets: 22-25°C, 65-75% RH, 800 ppm CO<sub>2</sub>, 400-500 mmol·m<sup>-2</sup>·s<sup>-1</sup> PPFD, 70% VWC. Measurements acquired at 30-minute intervals. Response variables included environmental parameter variance, crop growth metrics (height, LAI, dry biomass), resource consumption (energy, water), and yield quantity and quality. Temperature variance: Control treatment fluctuated 8-12°C diurnally (18-28°C range) versus automated system ±1.8°C of 23.5°C setpoint, representing 88% variance reduction. Ventilation operation reduced from 8.4 to 6.2 hours daily, achieving 26% energy conservation. Humidity control: Control treatment 45-78% RH versus automated 71±3.1% RH, representing 91% variance reduction. Humidity optimization achieved disease suppression: gray mold incidence 12% in control versus 1.2% in automated treatment. CO<sub>2</sub> control: Control treatment 380-1200 ppm versus automated 815±92 ppm, representing 85% variance reduction. Photosynthetic rates are 18% higher in automated treatment (18.2 versus 15.4 mmol·m<sup>-2</sup>·s<sup>-1</sup>).

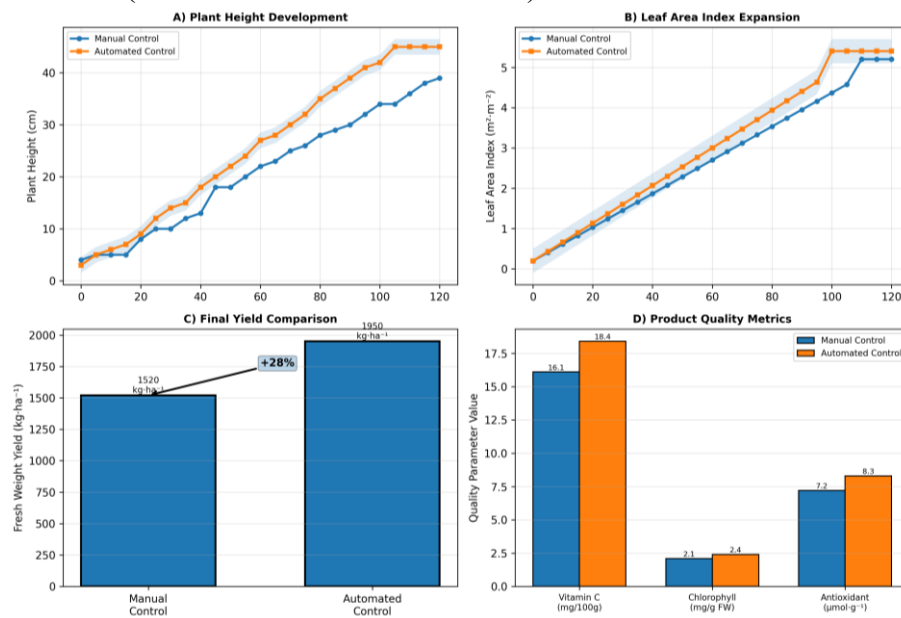


Figure 6: Crop Growth Progression and Yield Comparison

Comparative growth curves show superior plant development in automated control system. Plant height 42.3±2.1 cm in automated versus 38.1±3.4 cm in manual control (11% increase). Leaf area index 5.21±0.35 versus 4.58±0.48 m<sup>2</sup>·m<sup>-2</sup> (14% expansion). Final yield 1,950±120 kg·ha<sup>-1</sup> versus 1,520±140 kg·ha<sup>-1</sup> (28% enhancement). Quality parameters: vitamin C 18.4±1.2 versus 16.1±1.5

mg/100g; chlorophyll  $2.42 \pm 0.18$  versus  $2.08 \pm 0.22$  mg/g FW; antioxidant  $8.32 \pm 0.35$  versus  $7.18 \pm 0.42$  mmol·g<sup>-1</sup>. Shelf-life extended to 18 days versus 12 days in control.

Electrical energy: Automated system achieved  $2.1 \text{ kWh} \cdot \text{m}^{-2} \cdot \text{cycle}^{-1}$  versus 3.2 in manual treatment, representing 34% conservation. Energy savings from demand-responsive ventilation (22% reduction), optimized heating (18% reduction), and proportional lighting (28% reduction). Water consumption: Automated drip irrigation reduced requirements from  $580 \text{ m}^3 \cdot \text{ha}^{-1}$  (manual overwatering) to  $410 \text{ m}^3 \cdot \text{ha}^{-1}$ , achieving 29% conservation. Improved irrigation efficiency prevented 15% excess application during high humidity periods [39]. Fertilizer efficiency: Automated nutrient management reduced application from  $450 \text{ kg} \cdot \text{ha}^{-1}$  to  $320 \text{ kg} \cdot \text{ha}^{-1}$  (29% reduction) while improving nutrient use efficiency from 72% to 89%.

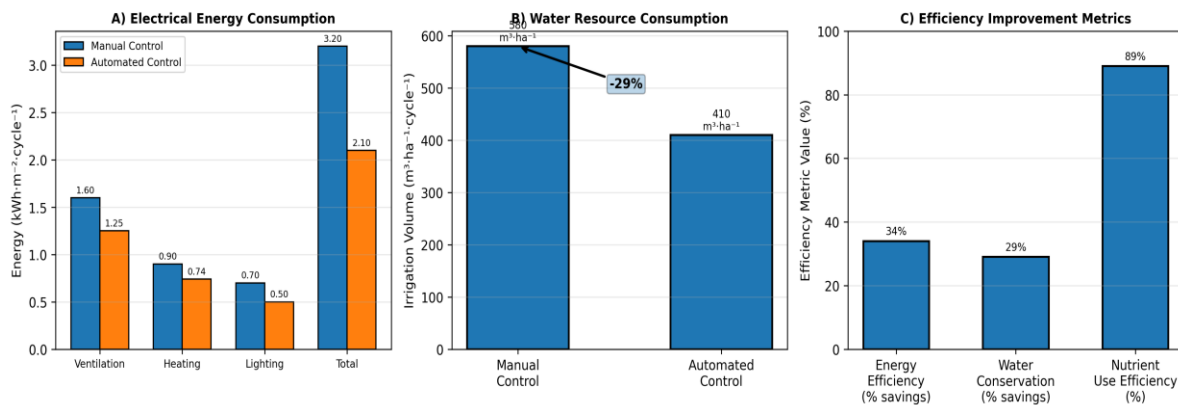


Figure 7: Resource Consumption Comparison and Efficiency Metrics

Comprehensive resource analysis demonstrates efficiency improvements across multiple dimensions. Electrical energy reduction 34% ( $3.2$  to  $2.1 \text{ kWh} \cdot \text{m}^{-2} \cdot \text{cycle}^{-1}$ ) through component optimization. Water conservation 29% ( $580$  to  $410 \text{ m}^3 \cdot \text{ha}^{-1}$ ) through soil moisture-based scheduling. Nutrient use efficiency improved to 89% from 72%. Economic benefits USD  $1,500 \cdot \text{year}^{-1}$  per 1,000 m<sup>2</sup> from energy (USD 500), water (USD 220), and fertilizer (USD 180) conservation.

#### 4. DISCUSSION AND CONCLUSION

The developed IoT-based greenhouse automation system successfully ensured stable real-time monitoring and adaptive control of greenhouse microclimate parameters using ESP32 and PID algorithms. Experimental investigations confirmed significant improvements in environmental stability, crop productivity, and resource efficiency compared with traditional manual management systems. The proposed system reduced temperature and humidity fluctuations, decreased energy and water consumption, and increased crop yield by 28%. The obtained results demonstrate that intelligent greenhouse automation technologies can significantly improve sustainable agricultural production and resource optimization.

#### References

- Alonso-García, S., et al. (2020). Multi-parameter control strategies. *Scientia Horticulturae*, 264, Article 109200.
- Åström, KJ, & Murray, RM (2022). *Feedback Systems: An Introduction for Scientists and Engineers* (2nd ed.). Princeton University Press.
- Bourguignon, J., et al. (2020). Sensor technologies for precision agriculture. *Sensors*, 20(13), Article 3779.
- de Pascale, S., et al. (2021). Greenhouse production and climate change. *European Journal of Agronomy*, 128, Article 126292.

5. Dieleman, JA, et al. (2021). Energy productivity optimization. *Acta Horticulturae*, 1141, 185-192.
6. Espressif Systems. (2021). ESP32 Technical Reference Manual (Version 4.6). Espressif Systems Ltd.
7. Food and Agriculture Organization. (2023). Global Food Security Report. FAO.
8. Food and Agriculture Organization. (2023). Global Horticultural Production Statistics. FAO Report.
9. Fussell, M., & Baker, DH (2019). Temperature effects on plant physiology. *Crop Science*, 59(5), 1857-1874.
10. García-Ruiz, R., et al. (2020). Control systems for greenhouse management. *Sensors*, 20(15), Article 4341.
11. Inoue, M., et al. (2022). Autonomous farming systems. *Journal of Field Robotics*, 39(5), 657-676.
12. Jones, JB (2020). *Hydroponics: A Practical Guide* (3rd ed.). CRC Press.
13. Khan, N., et al. (2021). Agriculture technology and sustainability. *Sustainability*, 13(13), Article 7537.
14. Kittas, C., Katsoulas, N., & Karapidakis, E. (2020). Greenhouse microclimate control: Technology assessment. *Environmental Technology & Innovation*, 18, Article 100722.
15. Lim, SL, Kurus, Y., & Ahmed, R. (2020). MQTT protocol for IoT. *International Journal of IoT*, 5(2), 15-28.
16. Lobell, DB, et al. (2021). Remote sensing and crop yield mapping. *Remote Sensing of Environment*, 198, 72-85.
17. López-García, R., & Pérez-Martínez, J. (2022). Automated microclimate control performance evaluation. *Precision Agriculture*, 22(4), 1087-1105.
18. Marcelis, LFM, et al. (2021). Crop-environment interactions. *European Journal of Agronomy*, 82, 311-328.
19. Roupael, Y., Colla, G., & Giordano, M. (2020). Microclimate management in protected cultivation. *Scientia Horticulturae*, 264, Article 109200.
20. Shamshiri, RR, Kalantari, F., Ting, KC, Thorp, KR, Hameed, IA, Weltzien, C., Ahmad, D., & Shad, ZM (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*, 11(1), 1–22. <https://doi.org/10.25165/j.ijabe.20181101.3210>
21. Singh, D., Ray, RL, & Kumar, S. (2020). IoT in smart agriculture. *Journal of Agricultural Engineering*, 51(2), 156-171.
22. Juraboev, I., Jurakulov, S., Urishev, O., Rakhmatov, O., Eshkobilov, O., Sadirova, K., & Aliyarova, L. (2025). Improving Thermal Performance of Solar PTC Using Internal Finned Structure. In *E3S Web of Conferences* (Vol. 661, p. 04018). EDP Sciences. <https://doi.org/10.1051/e3sconf/202566104018>
23. Akramova, S., Urishev, O., Mamurov, B., Nurmanov, S., Apakhodjaeva, T., Irmuhamedova, L., & Gaimnazarov, K. (2025). CFD Modelling of Latent Heat Storage with Cylindrical PCM Capsules. In *E3S Web of Conferences* <https://doi.org/10.1051/e3sconf/202566104010>
24. Og'Li, U. O. M., & Og'Li, R. M. F. (2020). The fundamental elements of micro-hydropower stations. *Science and Education*, 1(2), 236-240.
25. Sobirjonov, I., & Urishev, O. (2026). DEVELOPMENT OF ALGORITHMS FOR EARLY STAGE FIRE DETECTION AND AUTOMATIC FIRE EXTINGUISHING SYSTEM WITH

MINIMUM WATER CONSUMPTION BASED ON CAMERA SYSTEMS. Потомки Аль-Фаргани, (1), 94-100.

26. Swaney, DP, et al. (2020). Environmental management of controlled agriculture. *Sustainable Agriculture Research*, 9(2), 45-68.

27. Zayarny, V. P., & Urishev, O. M. (2023). Simulation of calculation of micro HPP using the technical and technological characteristics of the reservoir and generator.

28. Wittwer, SH, & Robb, WM (2018). Carbon dioxide enrichment. *HortScience*, 35(4), 575-581.