Jurnal Teknik Informatika (JUTIF)
P-ISSN: 2723-3863
E-ISSN: 2723-3871
Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

Designing AI - IoE Precision Farming to Create Sustainable Eco-Friendly Hydroponic Greenhouses

Murti Wisnu Ragil Sastyawan[1], Muhammad Ihsan Fawzi[*2], Radita Dwi Putera[3], Zakiyyan Zain Alkaf[4]. Muhammad Syhamsudin[5]

[1,3,4]Industrial Engineering, Universitas Jenderal Soedirman, Indonesia
[2]Informatics, Universitas Jenderal Soedirman, Indonesia
[5]Electrical Engineering, Universitas Jenderal Soedirman, Indonesia

Email: [2]ihsfwz@incomso.com

Received : Aug 13, 2025; Revised : Aug 20, 2025; Accepted : Aug 20, 2025; Published : Oct 23, 2025

Abstract

Conventional greenhouses, while boosting crop yields, face critical sustainability challenges due to high energy consumption and resource inefficiency, particularly in developing nations where manual management prevails. This research addresses these limitations by designing a comprehensive AI-IoE system architecture to create a smart, resource-efficient, and sustainable operational model for eco-friendly greenhouses. The development methodology involved a systematic process of requirements analysis, integrated hardware and software design, prototype assembly, and functional testing. The system utilizes an ESP32 microcontroller as its central control unit, integrating a suite of six sensors comprising light intensity, temperature, humidity, pH, Total Dissolved Solids (TDS), and CO_2 to monitor critical environmental parameters in real-time. This integration utilizes the extensive dataset for AI based predictive analysis, enabling the intelligent forecasting of environmental trends and proactive resource management. The research resulted in a complete system blueprint, including a detailed electronic circuit design, a production-ready Printed Circuit Board (PCB) layout, defined operational control logic, and an intuitive web-based dashboard for remote monitoring and management. This integrated AI-IoE architecture provides a tangible solution that surpasses previous fragmented approaches by offering holistic environmental control. The findings present a significant contribution to precision farming, establishing a scalable and efficient framework to enhance greenhouse productivity and ecological sustainability.

Keywords : *Eco-friendly greenhouse, Internet of Everything, Precision farming, Smart hydroponic, Sustainable agriculture, Wireless sensor networks*

1. INTRODUCTION

The global agricultural sector faces a dual challenge: increasing food production for a growing world population while simultaneously reducing its significant environmental impact. Conventional agricultural practices are a primary contributor to greenhouse gas emissions and environmental degradation, which accelerate climate change [1], [2]. This dilemma between productivity and sustainability demands disruptive innovations that can enhance crop yields while minimizing the ecological footprint [3]. Without such breakthroughs, food security and ecosystem stability will be increasingly threatened.

In response to this challenge, greenhouse agriculture has emerged as a key technology for production intensification. By creating a controlled micro-environment, greenhouses enable the optimization of plant growth factors [4], which translates into increased productivity, quality consistency, and year-round production capabilities [5]. Furthermore, these structures provide crucial protection against extreme weather and pest attacks, thereby mitigating the risk of crop failure [6].

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

However, despite their advantages, conventional greenhouses have a fundamental drawback: high energy consumption, making them one of the most energy-intensive agricultural business models [7]. Operational costs are inflated by the energy and resources required for environmental and nutrient control [8], [9]. Consequently, the energy demands make greenhouses a significant source of carbon emissions, an irony that contradicts the goal of sustainable agriculture [10]. In developing countries like Indonesia, this challenge is exacerbated by prevalently manual greenhouse management, leading to resource inefficiency and imprecise microclimate control [11].

To address these efficiency and sustainability challenges, the digital transformation towards the concept of a smart greenhouse, integrating the Internet of Everything (IoE) and Artificial Intelligence (AI), offers a promising solution. The Internet of Everything (IoE) is projected to deliver intelligent services while facilitating decision-making by connecting everything to the internet, extending the Internet of Things (IoT) concept from inter-device connection to intelligent connections among devices through technical advancements across disciplines like precision sensors, communication technologies, and data analytics [12], [13], [14], [15]. IoE expands connectivity beyond mere IoT devices to encompass intelligent connections involving sensors, actuators, and data analytics for automated decision-making [16], [17]. AI-based systems have been proven to support the reduction of resource consumption and increase crop yields [18]. This combination of AI and precision farming aligns with the Climate-Smart Agriculture framework, which aims to increase productivity, build climate resilience, and reduce emissions [19], [20]. Its implementation has been shown to drastically improve water and energy efficiency [21], provide socio-economic benefits [22], and comply with environmental regulations [23]. Through real-time monitoring and adjustment, farmers can create eco-friendly greenhouses that minimize energy use [24], [25].

Although the potential of this technology is widely acknowledged, a literature review reveals a significant research gap. The majority of studies tend to focus on optimizing isolated parameters, such as temperature and humidity control [26], [27], [28], [29], or air analysis [30], [31]. There is a scarcity of research designing a single system capable of simultaneously monitoring and managing all critical environmental parameters, such as light intensity, temperature, humidity, pH of the nutrient solution, Total Dissolved Solids (TDS), CO_2, and utilizing AI for dynamic prediction and decision-making. Therefore, this research is proposed to address this gap by designing and developing a comprehensive AI-IoE system architecture. The objective is to create a smart, resource-efficient, and truly sustainable operational model for greenhouses, thereby establishing an eco-friendly greenhouse.

2. METHOD

This research procedure is conducted systematically to ensure an integrated and precise IoE development system. The procedure commences with a system and requirements analysis based on a literature review, followed by functional testing of the entire system.

Based on the research flowchart in Figure 1, the research activities began with a system requirements analysis, which aimed to assess the needs of an IoE system specifically for greenhouses. At this stage, an in-depth literature study was also conducted regarding environmental parameters relevant to high-value crops. The next stage was system design, which included several important sub-stages. First, the technical specifications of the IoE system were formulated, including sensors, actuators, controllers, and communication devices. Database design was also crucial for determining the environmental data storage structure and integrating data from sensors in real time. Furthermore, architecture design was carried out, which included the creation of a workflow diagram as well as fuzzy control-based logic and algorithms. Next, the equipment was developed and assembled. At this stage, a prototype of the SmarTani system was assembled based on the design. Hardware components, such as sensors, actuators, and controllers, were tested to ensure optimal connectivity. Furthermore, software

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

was developed in accordance with the designed architecture to ensure seamless integration. The final stage is system functionality testing, where the entire system is tested to evaluate communication between components, measure device accuracy, and test the effectiveness of the control algorithm in managing environmental parameters in real time. The results of this testing will form the basis for the final evaluation of the developed SmarTani system.

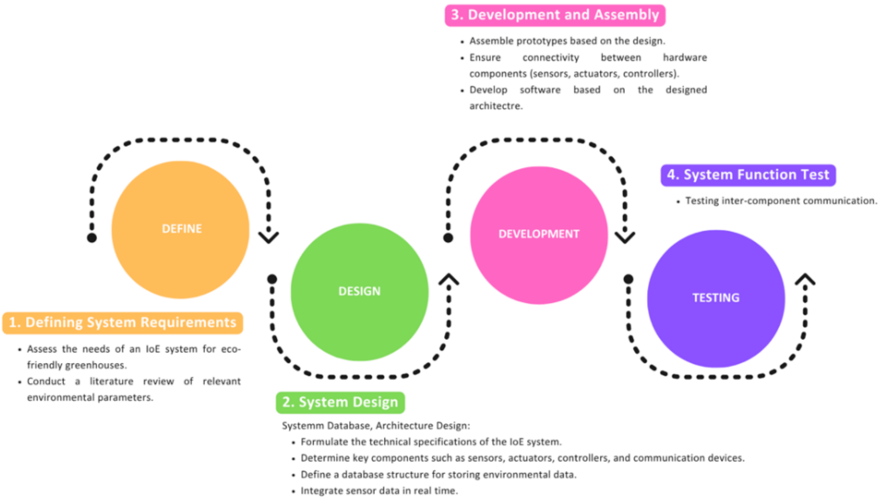

Figure 1. Research Flow

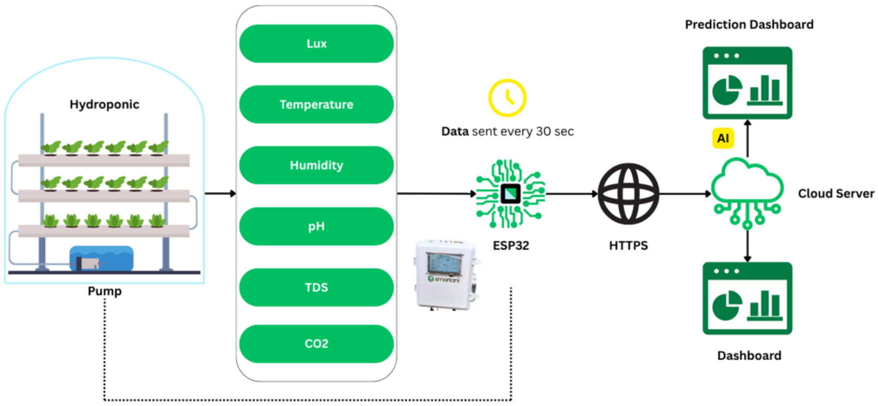

Figure 2. System Design of AI-IoE Hydroponic Greenhouse

This research focuses on the design and implementation of a smart hydroponic system integrated with IoE technology for real-time and automated monitoring and control of the growing environment. The workflow of the developed system, as illustrated in Figure 2, consists of several main component units.

2.1. Power Supply Unit

The power supply unit plays a crucial role in operating all devices and sensors [32], being designed to deliver a stable electrical supply. The primary source is 220 V AC electricity, which is connected to a power supply unit (PSU) to produce a 12 V DC output. This voltage is allocated to drive the solenoid valve and motor pump. A DC-DC step-down module is subsequently employed to reduce the voltage from 12 V to 5 V, providing power to the microcontroller and all connected sensors.

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

2.2. Control Unit

The system utilizes an ESP32 module as its central control unit. This module was selected due to its built-in Wi-Fi connectivity and robust processing capabilities. The ESP32 is responsible for executing the entire program logic, ranging from reading sensor data to transmitting commands to the actuators. This device can handle all data processing and control tasks within the greenhouse environment. The ESP32 microcontroller is widely employed in diverse applications owing to its powerful processing capabilities, wireless connectivity, and affordability.

2.3. Unit Sensor

Precision farming leverages various types of sensors to monitor and optimize farming practices [33]. For the real-time monitoring of key parameters, this system is equipped with a suite of sensors. These include a luminosity sensor to measure light intensity, temperature and humidity sensors, a pH sensor to measure acidity levels, a Total Dissolved Solids (TDS) sensor to gauge nutrient concentration, and a CO_2 sensor to monitor carbon dioxide. All sensors are interfaced with the input pins of the ESP32.

2.4. Software

Data gathered by the sensors is periodically transmitted to an IoE cloud platform. This platform serves to store the data and present it on a visual dashboard, which is remotely accessible via a web browser or a mobile application. Software dashboards play a crucial role in managing and visualizing data collected from sensors [34]. The dashboard displays real-time graphs and indicators for all monitored parameters (light, temperature, humidity, pH, TDS, CO_2), enabling users to effectively and efficiently monitor the hydroponic conditions within the greenhouse. Furthermore, the dashboard utilizes AI algorithms to analyze the data and offer actionable insights.

3. RESULT

This section presents the concrete results of the design and implementation process of an IoT-based monitoring and Could add comparison to existing systems to prove improvement. automation system for hydroponic cultivation. The results achieved encompass four main, interconnected aspects. First, the overall system architecture that defines the relationships between hardware components. Second, the physical implementation of the electronic circuit in the form of a Printed Circuit Board (PCB) design. Third, the operational control logic that forms the basis for the system to perform automation actions based on sensor data. Fourth, the web-based dashboard user interface (UI) designed for real-time system monitoring and management by users.

Figure 3 is a design architecture for IoE monitoring and hydroponic automation that was created. A total of six sensors are temperature, humidity, light, pH, TDS and CO_2 sensors. After the pH sensor is connected to the module, it is then connected with two R10K Ohm resistors to lower the electrical voltage level so that a higher input voltage produces a proportionally lower output voltage. Each sensor is connected to its respective sensor module which is then connected to a microcontroller where the microcontroller used is ESP32. ESP32 was chosen because it has better performance than Arduino, then ESP32 has better memory, and the ability to connect to Wi-Fi. ESP32 is connected with a capacitor to ensure that ESP32 always gets stable power so that it can run reliably without interruption.

This system obtains its primary power supply from an alternating voltage (AC) source which is then converted to a direct voltage (DC) of 12V by a power supply unit (PSU). The 12V voltage is then regulated down to 5V by a step-down DC-DC converter module to provide a stable power supply for the main components. The ESP32 sends low-power control signals to a relay module, which serves as an isolation interface for controlling high-power actuators. The actuators used include solenoid valves to regulate fluid flow and motor pumps for circulation or solution addition. Actuators can be used to

P-ISSN: 2723-3863
https://jutif.if.unsoed.ac.id
E-ISSN: 2723-3871
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

automate watering or nutrient irrigation. Positive and negative current cables are distinguished by color, where red is positive current and black is negative current. Other cable colors such as yellow, blue, brown, etc. are only for differentiating purposes to make the connection easier for the reader.

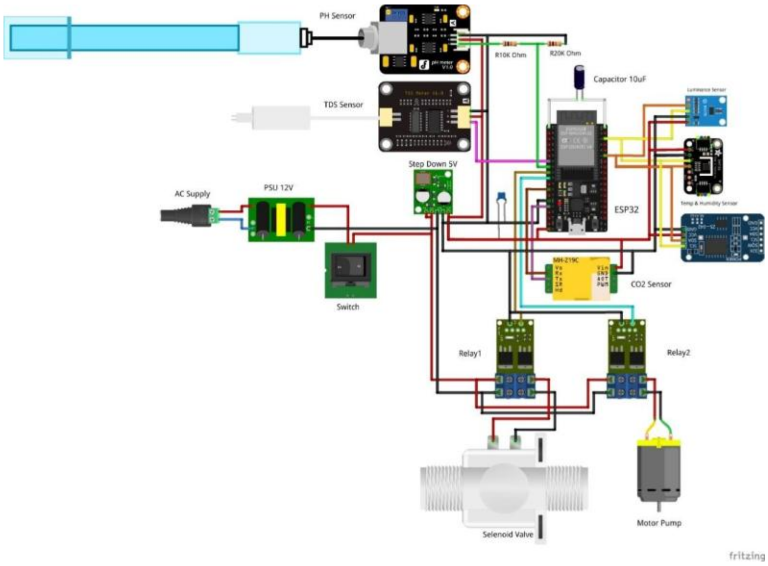

Figure 3. Architecture Design

Figure 4 shows the result of the physical design phase of the greenhouse IoE control system, namely the Printed Circuit Board (PCB) layout design. This design is the physical implementation of the previously created schematic diagram, which serves to convert the logical connections between components into physical conductive paths on a board. In this layout, the footprints for each component are strategically placed. In the center is the main area for mounting the ESP32 microcontroller module, which serves as the brain of the system. From this center, white copper traces are precisely routed to connect the ESP32 to various interface points. There are traces for sensor connectors (such as pH, TDS, temperature, and light), connectors for actuators (MOSFETs), and terminals for the power supply. This design has optimized component placement and trace width to ensure good signal integrity, minimize potential noise, and facilitate efficient current flow throughout the components. Four mounting holes in each corner are also included to facilitate installation of the circuit board within a protective housing or enclosure. The result of this design is a compact, integrated circuit board ready for fabrication and assembly, resulting in a functional and reliable hydroponic controller.

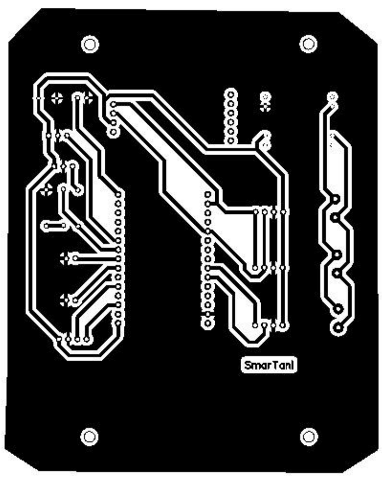

Figure 4. Printed Circuit Board (PCB) Layout Design

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

Table 1. Sensors and System Actions

Types of Sensors	Threshold Good Value	Action
Temperature	10°C - 34°C	Notification
Humidity	70-80%	Notification
Lux	200-400nmol (12,000 - 28,000 lux)	Notification
TDS	Early stage: 800-900 ppm Middle stage: 901-1200 ppm Harvest stage: 1201-1400 ppm	Turn on nutrient pump
pH	5.5 to 6.5	Notification
CO_2	700-1000 ppm	Notification

Table 1 outlines the operational parameters and control logic for a controlled environment system, most likely applied to modern agricultural systems such as hydroponics or smart greenhouses. This system uses a series of sensors to monitor vital conditions for plant growth in real time. Each parameter has a threshold value range that must be maintained. The ambient temperature is maintained between 10°C and 34°C, while relative humidity is maintained at 70-80%. Optimal light intensity (Lux) is in the range of 200-400 nmol (equivalent to 12,000-28,000 lux), and the acidity (pH) of the growing medium or nutrient solution is maintained between 5.5 and 6.5. The concentration of carbon dioxide (CO_2), essential for photosynthesis, is set at 700-1000 ppm. Specifically, the Total Dissolved Solids (TDS) parameter, which indicates nutrient concentration, has thresholds that are graded according to the plant's growth phase: early phase (800-900 ppm), mid-phase (901-1200 ppm), and harvest phase (1201-1400 ppm). The "Action" column defines the system's response when the sensor detects a value outside the threshold. For most parameters (temperature, humidity, lux, pH, and CO_2), the system will send a notification to the user. However, for TDS, the system will take immediate action by turning on the nutrient pump to adjust the solution concentration.

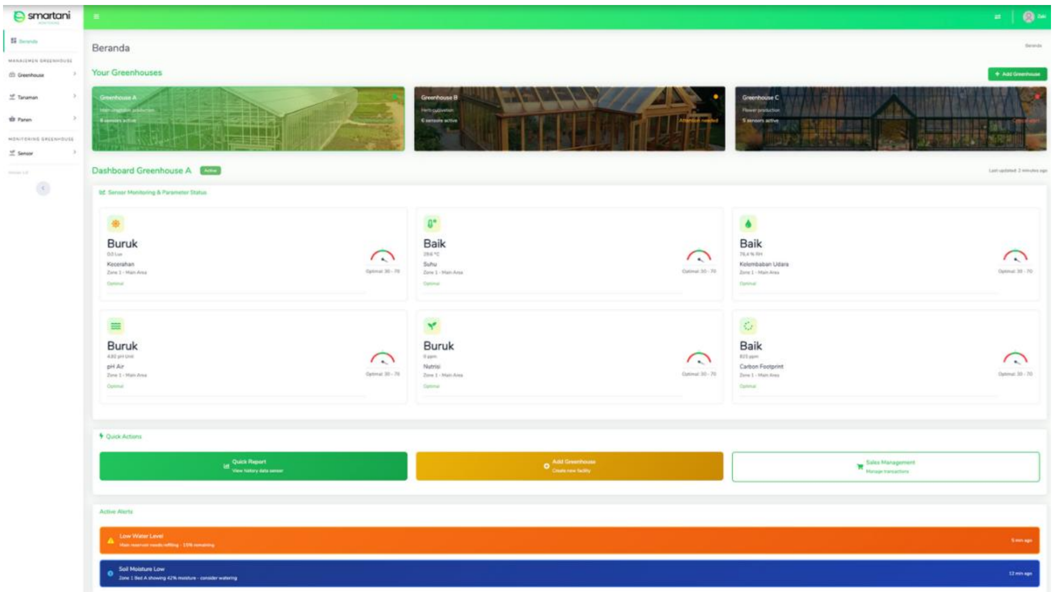

Figure 5. SmarTani Dashboard

To facilitate the monitoring and management of the melon hydroponic system, an intuitive and informative web-based dashboard user interface (UI) was designed, as shown in Figure 5. The dashboard in Figure x serves as a visual control center, presenting real-time data from all sensor nodes installed in the greenhouse. The central component of the dashboard is the "Sensor Monitoring" section, which

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

displays environmental parameters crucial for melon growth. Each parameter, such as Lighting, Air Humidity, Water pH, and other sensors is presented as an individual information card. Each card is equipped with a clear qualitative status indicator ("Good" or "Bad") and a visual gauge that shows the current parameter level relative to a predetermined optimal threshold. This approach allows users to quickly identify deviations from ideal conditions. In addition to passive monitoring, the dashboard is designed to support proactive management. The "Action Alerts" feature located at the bottom automatically displays warnings for critical conditions requiring immediate intervention, such as "Low Water Level." The dashboard also provides system management functionality through "Quick Actions," which include the ability to print reports (Print Report) for historical data analysis that can be used for predictive monitoring (AI). Additionally, quick actions can be used to add new greenhouse units.

As shown in Table 2, the proposed system exhibits several improvements over existing hydroponic monitoring systems. While conventional designs often rely on Arduino with limited performance and only a few sensors, this work integrates six key environmental parameters supported by ESP32 for faster processing and stable cloud connectivity. Furthermore, instead of merely providing notifications, the system automates nutrient control based on TDS thresholds and enhances decision-making through predictive AI functions. The optimized PCB layout also ensures higher reliability compared to breadboard-based prototypes, while the web-based dashboard offers a more intuitive and interactive interface for real-time monitoring and management. Overall, these enhancements make the system more robust, scalable, and suitable for sustainable smart greenhouse applications.

Table 2. Comaparasion of Proposed System With Existing Hydroponic Monitoring System

Feature/Aspect	Existing System	Proposed System
Controller	Arduino-based, limited memory, slower performance	ESP32 with higher memory, faster processing, WIFI
Sensor Coverage	Single or limited sensor (e.g., only pH & TDS)	6 integreted sensors (Temp, Humidity, Light, pH, TDS, CO_2)
Automation Capability	Mostly manual/notification only	Automated control for nutrient pump (TDS threshold)
Data Transmission	Local storage/manual logging	Real-Time cloud integration via HTTPS
Dashborad/Monitoring	Numeric display only	Web-Based dashborad with gauges, qualitative status, & quick action
Predictive Function (AI)	Absent	Integrated AI for predictive monitoring and alerts
Hardware Implemention	Breadboard/prototype wiring	Optimized PCB layout for reliability & campactness

4. DISCUSSIONS

This research presents a successfully designed holistic AI-Internet of Everything (AI-IoE) architecture for smart greenhouses, directly addressing the limitations of prior research. Previous studies have generally focused on a limited subset of parameters. For instance, many utilized microcontrollers like the ESP32 or Arduino to monitor discrete climate variables such as temperature and humidity, or separately managed pH and nutrient levels in hydroponic systems [35], [36], [37]. Furthermore, while some research has incorporated AI, its application has often been isolated to singular tasks, such as disease detection using Convolutional Neural Network (CNN) models [26], [38].

The primary contribution of this research is the simultaneous integration of six critical parameters, namely: temperature, humidity, light intensity, pH, Total Dissolved Solids (TDS), and CO_2, within a single, unified control dashboard. This integration enables the system to collect a significantly richer

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

dataset. The data is subsequently processed by an integrated AI model to provide holistic management recommendations, moving beyond single-function capabilities. This approach enhances operational efficiency and supports the overall sustainability of the greenhouse by offering a far more comprehensive overview of growth conditions, all monitored from the dashboard. The use of the ESP32 proved to be highly effective for handling inputs from this diverse sensor array and for real-time data transmission. Moreover, the implementation of a control loop that automatically activates actuators (e.g., pumps) based on data analysis transforms the system from a passive monitoring tool into an active and efficient management platform. With a design meticulously detailed down to the Printed Circuit Board (PCB) layout, this architecture is not only conceptually superior but also primed for realization as a compact and functional physical product.

Nevertheless, this research has its limitations. The evaluation was confined to functional testing. The system's long-term performance, including a quantitative validation of resource savings (water, energy) and improvements in crop productivity within a real-world greenhouse environment, has not yet been assessed. Therefore, an essential next step is to deploy the system over a full cropping cycle to collect empirical data, thereby validating its efficacy and economic feasibility.

Future research should therefore focus on several directions. First, long-term deployment across complete cropping cycles is essential to empirically validate improvements in yield, water use, and energy efficiency. Second, the AI component could be expanded beyond rule-based decision-making toward more advanced predictive and adaptive models, such as Reinforcement Learning (RL) or hybrid deep learning frameworks for early detection of plant stress and disease. Third, system adaptability across different crop types should be tested, as varying plants require distinct parameter thresholds and growth strategies. Fourth, integration with complementary IoT modules—such as renewable energy management or carbon emission tracking—could enhance sustainability and align the system with emerging carbon trading initiatives. Finally, user-centered refinements, including mobile application support, intuitive dashboards, and automated calibration features, would improve accessibility and encourage broader adoption by farmers.

5. CONCLUSION

This research was initiated to address the fundamental challenges of resource inefficiency and the absence of integrated management systems in greenhouse operations, particularly within the context of developing nations like Indonesia. To this end, the research has successfully designed and developed a comprehensive Artificial Intelligence-Internet of Everything (AI-IoE) system architecture tailored for precision agriculture within greenhouse environments. The engineered system integrates six key sensors for holistic environmental monitoring: temperature, humidity, light intensity, CO_2, pH, and Total Dissolved Solids (TDS). All sensor data is processed by an ESP32 microcontroller, which serves as the central control hub, and is linked to a cloud platform for real-time data visualization and analysis. Furthermore, the system is equipped with actuators (e.g., pumps) that enable the automation of corrective actions, such as data-driven nutrient adjustments, thereby establishing a smart and adaptive operational model. The principal deliverable of this research is a detailed blueprint, encompassing electronic circuit design, overall system architecture, and a production-ready Printed Circuit Board (PCB) layout. Consequently, the proposed system provides a tangible solution that addresses a significant gap in the literature and holds considerable potential to transform greenhouse operations, making them more efficient, productive, and eco-friendly.

CONFLICT OF INTEREST

The authors declares that there is no conflict of interest between the authors or with research object in this paper.

ACKNOWLEDGEMENT

The authors express their sincere appreciation to Universitas Jenderal Soedirman for the funding support provided for this research. Gratitude is also extended to all parties who served as the research objects and contributed to the successful completion of this study.

REFERENCES

[1] K. Appiah, J. Du, and J. Poku, "Causal relationship between agricultural production and carbon dioxide emissions in selected emerging economies," *Environ. Sci. Pollut. Res.*, vol. 25, no. 25, pp. 24764–24777, Sept. 2018, doi: 10.1007/s11356-018-2523-z.

[2] J. S. Kikstra *et al.*, "The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures," *Geosci. Model Dev.*, vol. 15, no. 24, pp. 9075–9109, Dec. 2022, doi: 10.5194/gmd-15-9075-2022.

[3] N. Istudor *et al.*, "Agriculture and the Twofold Relationship between Food Security and Climate Change. Evidence from Romania," *www.amfiteatrueconomic.ro*, vol. 21, no. 51, p. 285, May 2019, doi: 10.24818/EA/2019/51/285.

[4] G. P. A. Bot, "Selection Processes of (Changes in) Covered Cropping Patterns," in *Applied Agrometeorology*, K. Stigter, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 829–834. doi: 10.1007/978-3-540-74698-0_97.

[5] M. Farvardin, M. Taki, S. Gorjian, E. Shabani, and J. C. Sosa-Savedra, "Assessing the Physical and Environmental Aspects of Greenhouse Cultivation: A Comprehensive Review of Conventional and Hydroponic Methods," *Sustainability*, vol. 16, no. 3, p. 1273, Feb. 2024, doi: 10.3390/su16031273.

[6] N. S. Gruda and H. Fatnassi, "Greenhouse vegetable production from the point of view of climate change," *Acta Hortic.*, no. 1426, pp. 503–510, Apr. 2025, doi: 10.17660/ActaHortic.2025.1426.69.

[7] A. Badji, A. Benseddik, H. Bensaha, A. Boukhelifa, and I. Hasrane, "Design, technology, and management of greenhouse: A review," *J. Clean. Prod.*, vol. 373, p. 133753, Nov. 2022, doi: 10.1016/j.jclepro.2022.133753.

[8] A. Banakar, M. Montazeri, B. Ghobadian, H. Pasdarshahri, and F. Kamrani, "Energy analysis and assessing heating and cooling demands of closed greenhouse in Iran," *Therm. Sci. Eng. Prog.*, vol. 25, p. 101042, Oct. 2021, doi: 10.1016/j.tsep.2021.101042.

[9] G. Gugliuzza, A. Giovino, and G. Pachino, "First observation on tomato plant growth in an innovative soilless sustainable cultivation system in south of Italy," *Acta Hortic.*, no. 1377, pp. 687–694, Oct. 2023, doi: 10.17660/ActaHortic.2023.1377.84.

[10] R. M. Rees, "Air: Greenhouse gases from agriculture," in *Reference Module in Food Science*, Elsevier, 2025, p. B9780443159763000349. doi: 10.1016/B978-0-443-15976-3.00034-9.

[11] H. Yuliandoko, F. Panduardi, and A. Holik, "Monitoring System of Greenhouse Based on WSN and Auto Flushing Sensor Mechanism," in *2022 6th International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE)*, Yogyakarta, Indonesia: IEEE, Dec. 2022, pp. 234–238. doi: 10.1109/ICITISEE57756.2022.10057929.

[12] M. Miraz, M. Ali, P. Excell, and R. Picking, "Internet of Nano-Things, Things and Everything: Future Growth Trends," *Future Internet*, vol. 10, no. 8, p. 68, July 2018, doi: 10.3390/fi10080068.

[13] W. Rafique and J. Qadir, "Internet of everything meets the metaverse: Bridging physical and virtual worlds with blockchain," *Comput. Sci. Rev.*, vol. 54, p. 100678, Nov. 2024, doi: 10.1016/j.cosrev.2024.100678.

[14] G. Sciddurlo, P. Camarda, D. Striccoli, I. Cianci, G. Piro, and G. Boggia, "Markov chain-based analytical model supporting service provisioning and network design in the Social Internet of

Everything," *Comput. Netw.*, vol. 258, p. 111040, Feb. 2025, doi: 10.1016/j.comnet.2025.111040.

[15] K. Zhang, M. Li, B. Zhang, P. Chu, and G. Che, "High-accurate range acquisition for LFMCW radar with optimized maximum likelihood estimation towards Internet of Everything," *Phys. Commun.*, vol. 70, p. 102646, June 2025, doi: 10.1016/j.phycom.2025.102646.

[16] J. Devare and N. Hajare, "A Survey on IoT Based Agricultural Crop Growth Monitoring and Quality Control," in *2019 International Conference on Communication and Electronics Systems (ICCES)*, Coimbatore, India: IEEE, July 2019, pp. 1624–1630. doi: 10.1109/ICCES45898.2019.9002533.

[17] J. Yu *et al.*, "Sensing technology for greenhouse tomato production: A systematic review," *Smart Agric. Technol.*, vol. 11, p. 101020, Aug. 2025, doi: 10.1016/j.atech.2025.101020.

[18] J. N. K. Wah, "The Role of AI in Transforming Agriculture: Toward Sustainable Growth in an Era of Climate Change," Feb. 2025, doi: 10.5281/ZENODO.15587933.

[19] I. Arakelyan, A. Wreford, and D. Moran, "Can agriculture be climate smart?," in *Building a Climate Resilient Economy and Society*, K. N. Ninan and M. Inoue, Eds., Edward Elgar Publishing, 2017. doi: 10.4337/9781785368455.00019.

[20] M. Pathak, S. Patel, and S. Some, "Climate change mitigation and Sustainable Development Goals: Evidence and research gaps," *PLOS Clim.*, vol. 3, no. 3, p. e0000366, Mar. 2024, doi: 10.1371/journal.pclm.0000366.

[21] K. R. Sooryamol, S. Kumar, A. David Raj, and M. Sankar, "Smart Farming and Carbon Sequestration to Combat the Climate Crisis," in *Climate Crisis: Adaptive Approaches and Sustainability*, U. Chatterjee, R. Shaw, S. Kumar, A. D. Raj, and S. Das, Eds., in Sustainable Development Goals Series. , Cham: Springer Nature Switzerland, 2023, pp. 293–306. doi: 10.1007/978-3-031-44397-8_16.

[22] T. Nhat Lam Duyen, R. F. Rañola, B. O. Sander, R. Wassmann, N. D. Tien, and N. N. K. Ngoc, "A comparative analysis of gender and youth issues in rice production in North, Central, and South Vietnam," *Clim. Dev.*, vol. 13, no. 2, pp. 115–127, Feb. 2021, doi: 10.1080/17565529.2020.1734771.

[23] A. Flammini *et al.*, "Emissions of greenhouse gases from energy use in agriculture, forestry and fisheries: 1970–2019," *Earth Syst. Sci. Data*, vol. 14, no. 2, pp. 811–821, Feb. 2022, doi: 10.5194/essd-14-811-2022.

[24] N. Ben-Lhachemi, M. Benchrifa, S. Nasrdine, J. Mabrouki, M. Slaoui, and M. A. Azrour, "Effect of IoT Integration in Agricultural Greenhouses," in *Technical and Technological Solutions Towards a Sustainable Society and Circular Economy*, J. Mabrouki and A. Mourade, Eds., in World Sustainability Series. , Cham: Springer Nature Switzerland, 2024, pp. 435–445. doi: 10.1007/978-3-031-56292-1_35.

[25] A. Lachheb, R. Marouani, C. Mahamat, S. Skouri, and S. Bouadila, "Fostering Sustainability through the Integration of Renewable Energy in an Agricultural Hydroponic Greenhouse," *Eng. Technol. Appl. Sci. Res.*, vol. 14, no. 2, pp. 13398–13407, Apr. 2024, doi: 10.48084/etasr.6939.

[26] J. Contreras-Castillo, J. A. Guerrero-Ibañez, P. C. Santana-Mancilla, and L. Anido-Rifón, "SAgric-IoT: An IoT-Based Platform and Deep Learning for Greenhouse Monitoring," *Appl. Sci.*, vol. 13, no. 3, p. 1961, Feb. 2023, doi: 10.3390/app13031961.

[27] C. A. Hernández-Morales, J. M. Luna-Rivera, and R. Perez-Jimenez, "Design and deployment of a practical IoT-based monitoring system for protected cultivations," *Comput. Commun.*, vol. 186, pp. 51–64, Mar. 2022, doi: 10.1016/j.comcom.2022.01.009.

[28] B. Huang, "Research on the Application of Internet of Things Monitoring System in Greenhouse Flowers," in *2021 International Wireless Communications and Mobile Computing (IWCMC)*, Harbin City, China: IEEE, June 2021, pp. 1856–1859. doi: 10.1109/IWCMC51323.2021.9498699.

[29] K. Tatas *et al.*, "Reliable IoT-Based Monitoring and Control of Hydroponic Systems," *Technologies*, vol. 10, no. 1, p. 26, Feb. 2022, doi: 10.3390/technologies10010026.

[30] M. Lee, H. Kim, and H. Yoe, "ICBM-Based Smart Farm Environment Management System," in *Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing*,

Vol. 6, No. 5, October 2025, Page. 3983-3993
https://jutif.if.unsoed.ac.id
DOI: https://doi.org/10.52436/1.jutif.2025.6.5.5260

vol. 790, R. Lee, Ed., in Studies in Computational Intelligence, vol. 790. , Cham: Springer International Publishing, 2019, pp. 42–56. doi: 10.1007/978-3-319-98367-7_4.

[31] J. Nemčík, E. Mako, and T. Krajčovič, "Smart Indoor Greenhouse," in *7th Conference on the Engineering of Computer Based Systems*, Novi Sad Serbia: ACM, May 2021, pp. 1–2. doi: 10.1145/3459960.3461558.

[32] C. Maraveas, D. Piromalis, K. G. Arvanitis, T. Bartzanas, and D. Loukatos, "Applications of IoT for optimized greenhouse environment and resources management," *Comput. Electron. Agric.*, vol. 198, p. 106993, July 2022, doi: 10.1016/j.compag.2022.106993.

[33] H. Yin, Y. Cao, B. Marelli, X. Zeng, A. J. Mason, and C. Cao, "Soil Sensors and Plant Wearables for Smart and Precision Agriculture," *Adv. Mater.*, vol. 33, no. 20, p. 2007764, May 2021, doi: 10.1002/adma.202007764.

[34] M. Aarif K. O., A. Alam, and Y. Hotak, "Smart Sensor Technologies Shaping the Future of Precision Agriculture: Recent Advances and Future Outlooks," *J. Sens.*, vol. 2025, no. 1, p. 2460098, Jan. 2025, doi: 10.1155/js/2460098.

[35] A. Abu Sneineh and A. A. A. Shabaneh, "Design of a smart hydroponics monitoring system using an ESP32 microcontroller and the Internet of Things," *MethodsX*, vol. 11, p. 102401, Dec. 2023, doi: 10.1016/j.mex.2023.102401.

[36] M. Niswar, "Design and Implementation of an Automated IndoorHydroponic Farming System based on the Internet of Things," *Int. J. Comput. Digit. Syst.*, vol. 15, no. 1, pp. 337–346, Jan. 2024, doi: 10.12785/ijcds/150126.

[37] J. Seetaram, A. Bhavya, C. Tarun, and V. Sameera, "Internet of Things (IoT) Based Greenhouse Monitoring and Controlling System Using ESP-32," *IJARCCE*, vol. 13, no. 6, May 2024, doi: 10.17148/IJARCCE.2024.13605.

[38] H. A. Méndez-Guzmán *et al.*, "IoT-Based Monitoring System Applied to Aeroponics Greenhouse," *Sensors*, vol. 22, no. 15, p. 5646, July 2022, doi: 10.3390/s22155646.