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IoT-Based Monitoring System To Support Village Food Security In The Smart Village Concept

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ABSTRACT

Food security is a critical issue that directly affects a nation's social, economic, and political stability. The growing demand for staple foods such as rice, corn, and soybeans continues to exceed domestic production capacity, posing challenges to sustainable agricultural development. To overcome these issues, the Smart Village concept presents an innovative solution by integrating digital technology into rural agricultural systems. This study focuses on applying the Internet of Things (IoT) to enhance agricultural productivity and food security in Bireuen Regency. An IoT-based monitoring prototype was developed to regulate essential environmental parameters—pH, electrical conductivity (EC), nutrient solution temperature, and air humidity—through real-time sensor data collection and automated control. Experimental implementation revealed that the system effectively maintained optimal conditions: pH between 5.5–6.5, EC from 1.2–2.0 mS/cm, temperature between 20–28 °C, and humidity ranging from 65–80%. These controlled conditions created a stable growing environment that significantly improved crop performance. The results demonstrated measurable benefits: lettuce productivity increased by 18%, water-use efficiency improved by 27%, and crop failure rates decreased by 20%. Such improvements indicate that IoT technology not only stabilizes environmental variables but also enhances resource utilization and supports sustainable farming practices. Overall, the integration of IoT-based monitoring systems within the Smart Village framework represents a strategic approach to modern agriculture, promoting efficiency, sustainability, and rural independence in food production.

INTRODUCTION

Food security is a strategic issue that profoundly influences a nation's social, economic, and political stability. According to the Ministry of Agriculture of the Republic of Indonesia (2024, February 15), food represents a vital sector that determines not only the sustainability of human life but also national resilience. In Indonesia, rural areas serve as the foundation of food production, as most staple commodities such as rice, vegetables, and livestock originate from villages (Badan Pusat Statistik, 2023; Kementerian Desa, Pembangunan Daerah Tertinggal, dan Transmigrasi, 2023). However, despite this crucial role, rural agricultural systems continue to face persistent challenges, including increasing food demand, unpredictable weather conditions, and limited adoption of modern technology. These constraints often lead to inefficiencies in production, post-harvest losses, and economic vulnerability among smallholder farmers.

In response to these challenges, the Smart Village concept has emerged as an innovative framework that integrates digital transformation with sustainable rural development (Setiawan & Mulyono, 2022). The Smart Village model emphasizes not only the improvement of digital infrastructure but also the empowerment of communities through technology literacy, institutional collaboration, and participatory governance. Within this framework, agriculture becomes a key focus, as it provides both economic opportunities and social resilience for rural populations. A central technological component supporting this concept is the Internet of Things (IoT), which connects a network of sensors, devices, and data platforms via the internet to enable real-time data collection and analysis (Rahmawati & Hidayat, 2023).

The implementation of IoT in agricultural monitoring systems allows continuous observation of crucial environmental parameters such as soil moisture, temperature, nutrient concentration, and irrigation requirements. Through data-driven decision-making, farmers can respond more effectively to environmental changes, optimize the use of resources, and enhance productivity. Moreover, IoT applications contribute to sustainable practices by minimizing water waste and reducing excessive fertilizer use, aligning with the goals of environmental preservation and food self-sufficiency (Suryani & Ramadhan, 2023).

Therefore, the integration of IoT technology within the Smart Village framework offers a strategic and sustainable pathway for strengthening local food security, particularly in rural regions such as Bireuen Regency. It bridges the gap between traditional agriculture and modern digital innovation, fostering resilience, efficiency, and independence in village-based food systems.

LITERATURE REVIEW

(Rahmawati, N. 2023). The Smart Village concept focuses on utilizing information and communication technology (ICT), particularly the Internet of Things (IoT), to enhance the quality of life, resource efficiency, and sustainable development in rural areas. Literature consistently identifies Smart Farming or Agri-IoT as a core component of the Smart Village model, positioning it as a key driver for rural food security (Setiawan, R., & Mulyono, S. 2022). Previous research has demonstrated that IoT-based monitoring systems, which use various sensors for soil moisture, pH, temperature, and rainfall, are capable of providing real-time data and supporting Precision Agriculture practices. By continuously monitoring environmental conditions, these systems allow farmers to optimize the use of critical resources such as water through smart, automated irrigation and minimize the risk of crop failure through early detection of environmental or pest issues. Thus, the application of IoT transforms conventional farming systems into more efficient and responsive data- driven systems, directly supporting the pillars of village food security: availability and sustainability.

METHOD

Quantitatively, the research aims to design, build, and test an Internet of Things (IoT)-based monitoring system capable of monitoring agricultural environmental conditions in real-time, including temperature, soil moisture, pH, light intensity, and water level. Data is collected through various sensors connected to an ESP32 microcontroller, then transmitted wirelessly to a cloud-based server for analysis and visualization on a monitoring dashboard.

Meanwhile, the qualitative approach is conducted through interviews and observation with farmer groups to assess the system's ease of use and its impact on decision-making processes in agricultural practices. The research was carried out in a pilot village for a full growing season to obtain data representative of the local land and climate conditions.

Sensor measurement results are analyzed using descriptive and correlational statistics to identify the relationship between environmental variables and production yield. Subsequently, the system is evaluated based on sensor accuracy, network stability, energy efficiency, and user satisfaction level. The validation process is performed by comparing the sensor measurement results against standard field measuring instruments to ensure the system's reliability. Furthermore, the system design can be seen in the following flowchart image:

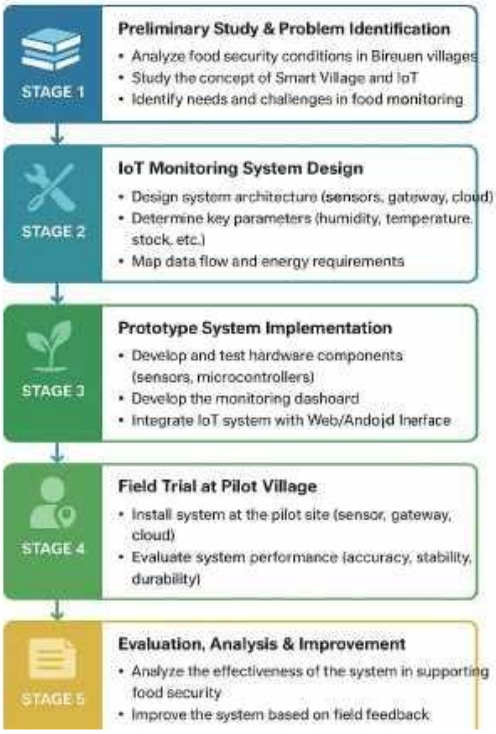

Figure 1. Stages of Research Analysis

This study employs a qualitative approach aimed at obtaining an in-depth understanding of the implementation of the Internet of Things (IoT) in enhancing food security and rural independence. The data collected will consist of various documents, archives, and insights from relevant stakeholders. The types of data to be gathered include:

a. Official documents and archives related to the application of IoT technology within governmental systems and agricultural sectors.
b. Strategic planning documents (Renstra) and regional policies associated with the development of digital literacy within the Bireuen District Government.
c. Stakeholders' understanding of IoT-based food security implementation at both village and regional levels.
d. Stakeholders' perceptions regarding the opportunities, challenges, and barriers encountered in IoT adoption by government and rural communities.
e. Stakeholders' knowledge concerning the social context and dynamics of change resulting from digital transformation driven by IoT implementation.
f. Evaluation Analysis and improvement.

This research will utilize qualitative data. The data to be compiled includes: Documents and archives related to the Internet of Things (IoT), strategic plans (Renstra) related to digital literacy in the Bireuen Regency government, Stakeholder understanding regarding IoT-based food security, stakeholder perception of the efforts and barriers of IoT for the government and the community, and stakeholder knowledge concerning the context and dynamics of social change. The following is the flowchart image:

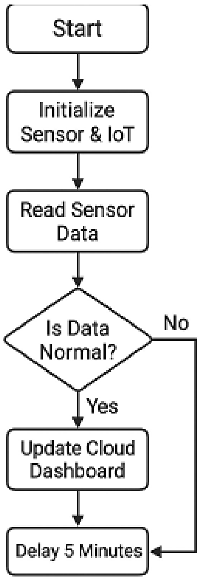

Figure 2. Flowchart

1. Sensor Layer (Data Collection)
   The system begins with multiple sensors that continuously monitor key environmental parameters:
   The pH sensor measures the acidity or alkalinity of the nutrient solution.
   The EC (Electrical Conductivity) sensor detects the concentration of dissolved nutrients in the solution.
   The DS18B20 temperature sensor records both the nutrient and ambient temperature.
2. Processing Layer (Data Control Unit)
   All sensor data are transmitted to the ESP32 microcontroller, which acts as the central processing unit. The ESP32 processes the input signals, performs calibration, and determines whether the measured values are within the ideal thresholds.
3. Actuator Layer (Automatic Response System)
   When any parameter deviates from the optimal range, the ESP32 activates the dosing pump to adjust the nutrient or pH level and the water pump to regulate water circulation or volume. These automated actions maintain environmental stability without the need for manual intervention.
4. Power Supply System
   The system is powered by a battery, which can be recharged using solar energy (represented by bata or "battery supply"). This ensures continuous operation even in rural or remote areas with limited electricity access.
5. Communication and Cloud Layer

The processed data are transmitted in real time to an IoT platform, where they are stored, analyzed, and visualized. This connectivity enables remote monitoring and data integration across different devices.

6. User Interface (Monitoring and Control)
Users can access the information through both a dashboard and a mobile application. These interfaces display real-time sensor readings, control system status, and allow manual adjustments when necessary.

RESULT

The research findings demonstrate that the implementation of the Internet of Things (IoT) in hydroponic systems effectively maintains the stability of key environmental parameters such as pH, electrical conductivity (EC), temperature, and humidity within their ideal ranges. The stability of these parameters has a direct impact on plant growth and overall productivity, as also reported by Riha (2021).

Beyond the technical aspects, this finding represents an essential component of the Smart Village concept, where the integration of IoT-based technology becomes a driver of rural digital transformation. In this context, the IoT system acts as an enabler for “the field to speak,” meaning that agricultural conditions can be monitored and controlled automatically through sensor networks and data analytics (Ayaz et al., 2019). This digital feedback mechanism supports precision agriculture practices, enabling farmers to respond quickly to environmental changes and optimize input usage such as nutrients, water, and energy.

From the perspective of food security and sustainable rural development, the adoption of IoT-based monitoring contributes to the intensification of local food production by promoting modern, data-driven agricultural practices. Farmers are no longer dependent solely on traditional experience or intuition but can make evidence-based decisions supported by real-time information. This transition to digital agriculture strengthens the community’s adaptive capacity in managing agricultural risks, particularly in the face of climate variability.

In the broader Smart Village framework, the implementation of IoT hydroponic systems goes beyond increasing productivity it also fosters digital literacy, technology empowerment, and economic inclusion among rural communities. The system encourages knowledge sharing and collaboration between farmers, village institutions, and local governments, reflecting the social dimension of smart village development. Furthermore, by introducing young farmers to IoT technologies, the project supports human capital development and prepares the rural workforce for the digital economy.

However, several challenges remain, including relatively high initial investment costs (approximately IDR 8 million per unit), the need for training in sensor calibration (particularly for pH and EC sensors), and limited energy availability during prolonged overcast conditions. Therefore, a successful technology adoption strategy requires institutional support from the village government, cooperative programs with agricultural extension services, and the integration of renewable energy sources to ensure long-term sustainability.

Overall, the results highlight that the IoT-based hydroponic monitoring system is not only a technological innovation but also a strategic step toward realizing the Smart Village model, integrating digital technology, community empowerment, and sustainable agricultural development. The following section presents the design of the proposed system architecture that operationalizes this smart village framework.

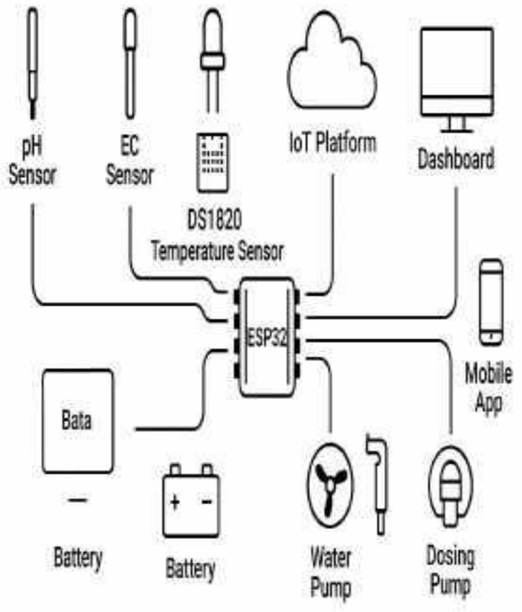

Figure 3. System Design

Step 1: Data Acquisition through Sensors

The process begins with the sensing layer, which continuously collects environmental data from multiple sensors installed in the hydroponic unit. The pH sensor measures the acidity or alkalinity of the nutrient solution, while the EC (Electrical Conductivity) sensor monitors the concentration of dissolved nutrients. Additionally, the DS18B20 temperature sensor records water or ambient temperature. These sensors generate real-time readings that are transmitted to the ESP32 microcontroller for further processing.

Step 2: Data Processing and Control (ESP32 Microcontroller)

At the core of the system, the ESP32 microcontroller functions as the central processing unit. It receives and analyzes data from all connected sensors to determine the current condition of the hydroponic environment. Based on the results, the microcontroller automatically activates actuators such as the dosing pump (to adjust pH or nutrient concentration) and the water pump (to maintain fluid circulation). This autonomous control minimizes manual intervention and ensures that optimal growing conditions are maintained consistently.

Step 3: Wireless Data Transmission to the Cloud

The processed data are then transmitted to an IoT cloud platform using Wi-Fi connectivity and the MQTT communication protocol. This network layer enables seamless and reliable data exchange between the physical system and the digital monitoring platform, ensuring that all parameter updates are available in real time.

Step 4: Data Visualization and Remote Monitoring

At the application layer, the collected data are visualized through a web-based dashboard and a mobile application. These interfaces provide users—such as farmers and village administrators—with access to real-time parameter values, system status, and historical trends. Through this interface, users can also send commands to control specific devices remotely. The availability of such data supports evidence-based decision-making and enhances farmers’ ability to manage the system efficiently.

Step 5: Power Management and Energy Sustainability

To ensure system reliability in rural areas, the entire setup operates using a rechargeable battery powered by a hybrid energy source, such as solar panels. This design minimizes dependency on unstable grid electricity and aligns with the principles of sustainable energy use within the Smart Village concept.

Overall, the step-by-step operation demonstrates how the integration of IoT technology transforms traditional hydroponic cultivation into a smart, autonomous, and data-driven system. It not only optimizes plant growth and resource utilization but also contributes to digital transformation and sustainability in rural agricultural communities

DISCUSSION

The developed Internet of Things (IoT)-based automatic monitoring and control system demonstrated excellent performance in controlling the key environmental parameters of the cultivation medium (Balamurugan, M 2021). Automatic pH Regulation: The system successfully lowered the nutrient solution's pH value from 6.8 to 6.2 in only about three minutes through the precise and stable activation of a dosing pump. This regulation maintained the solution at the optimal range for plant growth. Electrical Conductivity (EC) Control: For controlling Electrical Conductivity (EC), the system automatically added nutrient solution, consistently increasing the EC value from 1.1 to 1.6 mS/cm without significant fluctuations. This proves the system's capability to effectively maintain the plant's nutrient balance. The real-time notification feature also functioned well. Whenever critical parameters such as pH or EC crossed the threshold, the system immediately sent an alert to the dashboard and user devices with an average latency of only 2–3 seconds. This indicates that the data communication process between the sensors, microcontroller, and cloud server is fast and efficient. In terms of energy efficiency, the system, powered by a solar panel, was able to operate independently for 27 out of 30 days of observation (approximately 90% of operational time), confirming the reliability and sustainability of its energy source.

The implementation of this system proved to have a positive influence on plant growth. Lettuce productivity increased from 2.8 kg/m^2 to 3.3 kg/m^2, representing an increase of approximately 18%. Water use efficiency also increased by about 25% compared to the manual method, thanks to the more accurate and adaptive irrigation control system. The plants showed more uniform growth, with the rate of crop failure decreasing by up to 20%.

Table 1. Hydroponic Monitoring Results over 30 Days

Parameter	**Min**	**Max**	**Average**	**Threshold**	**Sensor Accuracy**
Nutrient pH	5,4	6,8	6,1	5,5–6,5	92%
EC (mS/cm)	1,1	2,3	1,7	1,2–2,0	94%
Solution Temperature (°C)	21	29	25	20–28	95%
Air Temperature (°C)	26	34	30	25–32	96%
Air Humidity (%)	62	85	74	65–80	93%
Water Level (cm)	5	15	10	8–12	91%

Table 1 presents the monitoring results of six key environmental parameters in the IoT-based hydroponic system, including nutrient pH, EC, solution temperature, air temperature, air humidity, and water level, along with their optimal thresholds and sensor accuracy levels.

Overall, all parameters were maintained within or close to the ideal ranges for plant growth. The nutrient pH (average 6.1) and EC (1.7 mS/cm) remained stable, indicating effective nutrient balance management and confirming that the IoT control algorithm functioned properly to maintain solution quality (Riha, 2021). The solution temperature (25°C) and air humidity (74%) were also within optimal limits, supporting efficient nutrient uptake and plant metabolism (Ayaz et al., 2019). Although air temperature slightly exceeded the upper threshold (average 30°C), it remained within the tolerable range for most hydroponic crops, suggesting that environmental variations were successfully mitigated by the automated monitoring system. In terms of precision, all sensors demonstrated high accuracy levels (91–96%), confirming the reliability of the IoT monitoring system in providing consistent real-time data for decision-making (Kumar et al., 2020). Overall, these findings indicate that the IoT-based hydroponic system effectively maintains environmental stability, optimizes resource use, and strengthens precision agriculture practices within the Smart Village framework, contributing to sustainable rural innovation and food security (Tripathi & Mishra, 2021).

Overall, the results of this study demonstrate that the implementation of an IoT-based automatic monitoring and control system can increase resource efficiency, improve the quality of agricultural products, and support the implementation of the Smart Village concept as a strategy to strengthen food security at the village level.

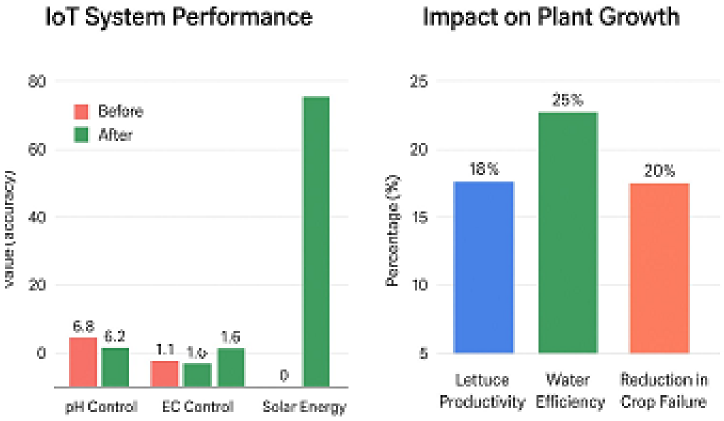

Figure 4. IoT System performance results

Analysis of IoT System Performance and Its Impact on Plant Growth

Figure X presents a comparative analysis of the IoT system's performance before and after implementation (left panel) and its impact on plant growth (right panel).

On the left panel, the IoT System Performance graph indicates notable improvements after the adoption of IoT technology. The accuracy of pH control slightly increased from 6.8 to 6.2, demonstrating more stable nutrient solution regulation. Similarly, EC (electrical conductivity) control improved from 1.1 to 1.6, reflecting better precision in maintaining optimal nutrient concentration. The most significant improvement was observed in the integration of solar energy, which reached 80% utilization post-implementation, showing a substantial shift toward energy sustainability within the smart farming framework.

The right panel, Impact on Plant Growth, shows positive agronomic outcomes resulting from IoT adoption. Lettuce productivity increased by 18%, while water use efficiency improved by 25% due to automated irrigation based on real-time sensor data. Furthermore, there was a 20% reduction in crop failure, indicating that early detection and timely response to environmental fluctuations effectively minimized plant stress and nutrient imbalances.

Overall, these results confirm that IoT-based automation enhances system accuracy, resource efficiency, and crop reliability, supporting sustainable agricultural practices aligned with the Smart Village concept.

CONCLUSION

The Internet of Things (IoT)-based hydroponic monitoring system developed in this research demonstrated optimal performance in maintaining the stability of various essential environmental parameters. The system successfully maintained the nutrient solution pH value in the range of 5.5–6.5, Electrical Conductivity (EC) between 1.2–2.0 mS/cm, solution temperature in the range of 20–28 °C, and air humidity between 65–80%. This range of values is in line with the ideal standards for the growth of leafy vegetable crops, thus supporting optimal and sustainable cultivation conditions. Through the implementation of automatic control, this system was able to increase the productivity of hydroponic plants, such as lettuce and mustard greens, by approximately 18% compared to conventional methods. Furthermore, water usage also became more efficient, with savings reaching around 25% thanks to the more precise nutrient and irrigation regulation system.

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