Type of Contribution:
Editorial
Research Paper
Review Paper
Case Study

ENERGY: JURNAL ILMIAH ILMU-ILMU TEKNIK
Vol. 16, No. 2 (2026) pp 519-530
DOI: 10.51747/energy.v16i2.p519-530
E-ISSN: 2962-2565

This article contributes to:
SUSTAINABLE DEVELOPMENT GOALS
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

IoT-Based Automated Irrigation for Pak Choy Using Aquaculture Wastewater

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Abstract

Efficient irrigation management and nutrient utilization are essential factors in improving pak choy productivity. This study proposes an Internet of Things (IoT)-based automated irrigation system that integrates an ESP32 microcontroller, soil moisture sensors, rain sensors, Telegram Bot, and n8n workflow automation. The system applies growth-stage-based irrigation scheduling and utilizes catfish pond wastewater as an alternative nutrient source. Irrigation volumes were dynamically adjusted according to plant growth stages, consisting of 0.65 L (days 1–14), 0.63 L (days 15–21), and 0.37 L (days 22–35). System performance was evaluated through communication testing, confusion matrix analysis, and plant growth observations. Experimental results showed average end-to-end delays of 6.0 s for Telegram communication and 11.3 s for n8n integration, with an average command latency of 2.779 s. The irrigation decision mechanism achieved 90% accuracy, 88.9% precision, and 91% recall. Furthermore, pak choy irrigated with catfish pond wastewater demonstrated superior growth performance, reaching 16 cm plant height, 20 leaves, and 81 g harvest weight, compared with 14 cm, 16 leaves, and 67 g under conventional irrigation. These findings demonstrate that the proposed system provides reliable irrigation automation while supporting sustainable agriculture through the reutilization of aquaculture wastewater.

Keywords: Automated irrigation, ESP32, IoT, n8n, pak choy, smart agriculture.

Article Info
Submitted: 2026-06-30
Revised: 2026-08-31
Accepted: 2026-09-25
Published: 2026-09-27

Publisher
Universitas Panca Marga

1. Introduction

Modern agricultural research focuses heavily on the integration of Internet of Things (IoT) frameworks to optimize yield metrics and resource distribution. A primary area of study is the optimization of irrigation dynamics in vegetable cultivation, where traditional empirical scheduling—relying on manual observation rather than real-time sensor metrics—presents significant operational challenges.

Current research addresses the systemic inefficiencies of this manual approach, specifically its failure to integrate dynamic environmental variables, soil matric potential, meteorological data, and crop phenology stages. Consequently, standard research objectives center on mitigating the quantifiable risks associated with empirical irrigation, namely structural water waste, destabilized soil moisture profiles, and depressed agricultural output.

Pak choy (Brassica rapa L.) is one of the most widely cultivated leafy vegetables due to its short cultivation cycle and high market demand. Previous studies reported that pak choy requires regular irrigation, particularly during its vegetative growth phase, and optimal soil moisture should be maintained at approximately 80% to support healthy growth and biomass production [1], [2], [3]. Furthermore, irrigation requirements vary according to plant growth stages, requiring different water volumes throughout the cultivation period [2]. Failure to provide appropriate irrigation may negatively affect plant height, leaf development, and harvest yield.

Recent advancements in Internet of Things (IoT) technology have enabled the development of automated irrigation systems using microcontrollers, environmental sensors, wireless communication, and cloud-based monitoring platforms. Technologies such as ESP32, soil moisture sensors, rain sensors, and web automation services have been successfully applied to support smart agriculture applications [4], [5], [6], [7]. Automated irrigation systems can perform real-time monitoring and decision-making processes, thereby reducing human intervention while improving irrigation accuracy and efficiency.

In addition to irrigation management, sustainable nutrient utilization has become an important issue in modern agriculture. Wastewater generated from catfish farming contains essential nutrients such as nitrogen, phosphorus, and potassium that are beneficial for plant growth [8], [9]. Previous research demonstrated that catfish pond wastewater can significantly improve plant height, leaf number, and biomass production when utilized as liquid fertilizer [5]. However, most existing studies focus only on evaluating the agronomic effects of wastewater application, while limited attention has been given to its integration with IoT-based irrigation automation systems.

Several previous studies have developed IoT-based irrigation systems using soil moisture sensors and rain detection mechanisms [3], [4]. Other studies investigated the use of catfish wastewater as an alternative nutrient source for vegetable cultivation [5]. Nevertheless, research combining automated irrigation, growth-stage-based water allocation, cloud workflow automation, and nutrient-rich catfish wastewater within a single integrated system remains limited. Furthermore, many existing systems provide only local monitoring capabilities and lack automated data logging and reporting mechanisms.

To address these limitations, this study proposes an IoT-based automated irrigation system for pak choy cultivation utilizing ESP32 DevKitC V4, soil moisture sensors, rain sensors, and RTC DS3231 modules. The system integrates Telegram Bot and n8n workflow automation to provide real-time monitoring, notification services, and automatic data recording [10], [11]. Unlike previous studies, the proposed system incorporates growth-stage-based irrigation scheduling and utilizes catfish pond wastewater as an alternative irrigation source containing natural nutrients beneficial for plant growth [5].

The objectives of this research are: (1) to design and implement an IoT-based automated irrigation system integrated with n8n and Telegram; (2) to evaluate the performance of the irrigation decision-making mechanism using confusion matrix metrics [12], [13]; (3) to analyze communication performance through end-to-end delay measurements [9]; and (4) to investigate the effects of catfish pond wastewater on pak choy growth parameters, including plant height, leaf number, and harvest weight. The proposed system is expected to contribute to sustainable smart agriculture by improving irrigation efficiency, reducing manual labor, and promoting the beneficial reuse of aquaculture wastewater.

2. Methods

2.1 Research Design and Object

This study employed an experimental approach to design, implement, and evaluate an Internet of Things (IoT)-based automated irrigation system for pak choy cultivation. The proposed system was developed to automate irrigation activities based on soil moisture conditions, rainfall detection, irrigation schedules, and plant growth stages while integrating real-time monitoring and reporting functions through Telegram and n8n. The research process consisted of literature review, system design, hardware and software development, sensor calibration, system implementation, performance evaluation, and plant growth observation. The overall research stages are illustrated in **Figure 1**

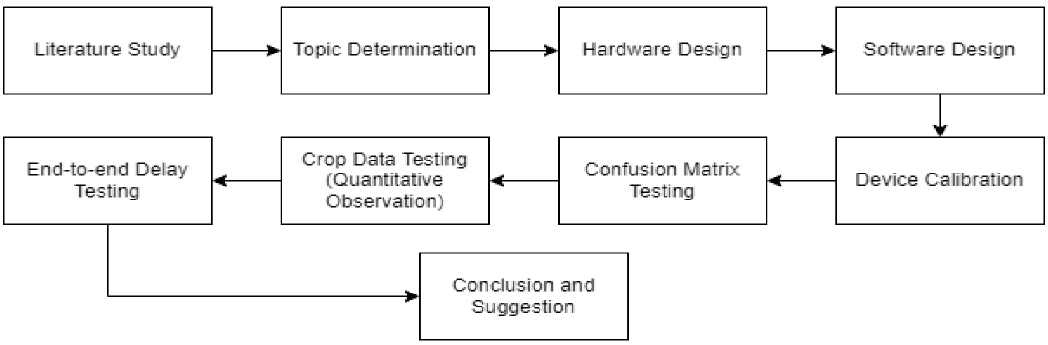

Figure 1. Research Stage for IoT-Based Automated Irrigation for Pak Choy Using Aquaculture Wastewater

2.2 System Architecture

The automated irrigation system was built using an ESP32 DevKitC V4 microcontroller as the central processing unit. The hardware subsystem consisted of resistive-type soil moisture sensors, a rain sensor, an RTC DS3231 module, relay modules, and two 12 V peristaltic pumps. The software subsystem utilized Arduino IDE for embedded programming, Telegram Bot for user notifications, and n8n for workflow automation and data management.

Sensor data collected from the field were processed by the ESP32 to determine irrigation actions according to predefined decision rules. The microcontroller also transmitted monitoring information through internet connectivity to Telegram and n8n services. Irrigation activities were performed automatically by activating the peristaltic pumps through relay control. The overall architecture of the proposed system is shown in Figure 2.

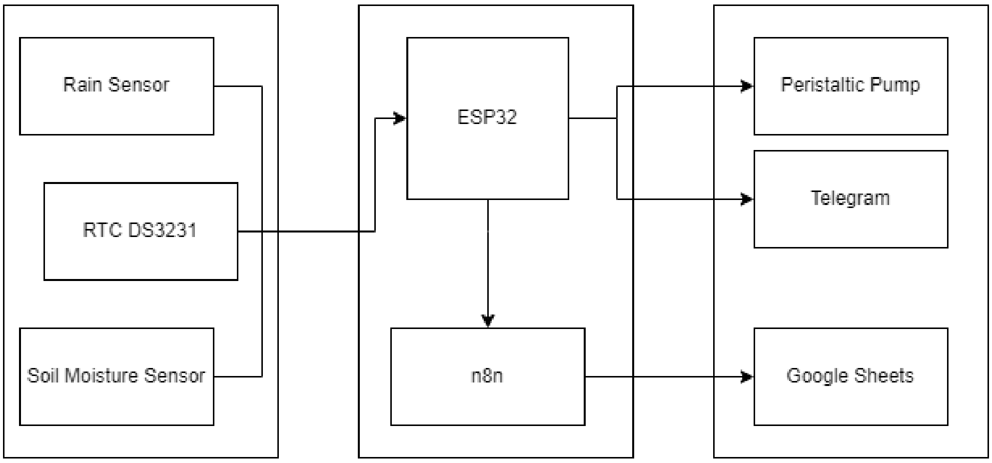

Figure 2. System Block Diagram

2.3 Irrigation Mechanism

The irrigation mechanism was designed according to the growth stages of pak choy during a 35-day cultivation period. Different irrigation volumes were applied to each growth stage to maintain adequate soil moisture and support plant development. During the early stage of the plant, water requirement is higher since it is in dimensional growth and increased evaporation and transpiration period. Entering later stage, this requirement is lower. Table 1 presents the irrigation volumes applied during the cultivation period.

Table 1. Irrigation volume based on growth stage

No	Growth Stage	Cultivation Day	Volume (L)
1.	Early Stage	1-14	0.65
2.	Middle Stage	15 -21	0.63
3.	Final Stage	22-35	0.37

The system performed irrigation checks twice daily at 07:00 and 16:00. During each scheduled session, the ESP32 evaluated soil moisture conditions, rainfall status, and plant age before determining whether irrigation should be executed. The irrigation volume was automatically adjusted according to the current growth stage.

2.4 Telegram and n8n Integration

To support real-time monitoring and automatic data recording, the proposed system was integrated with Telegram Bot and the n8n workflow automation platform. The ESP32 transmitted sensor readings and irrigation status information through HTTPS requests to a Webhook endpoint configured in n8n.

The received data were processed automatically and stored in Google Sheets for historical record management. Telegram Bot provided periodic reports containing environmental conditions, irrigation status, soil moisture information, and cultivation progress. Additional notifications were generated for specific events such as harvest readiness and system reset operations. The workflow architecture is illustrated in **Figure 3.**

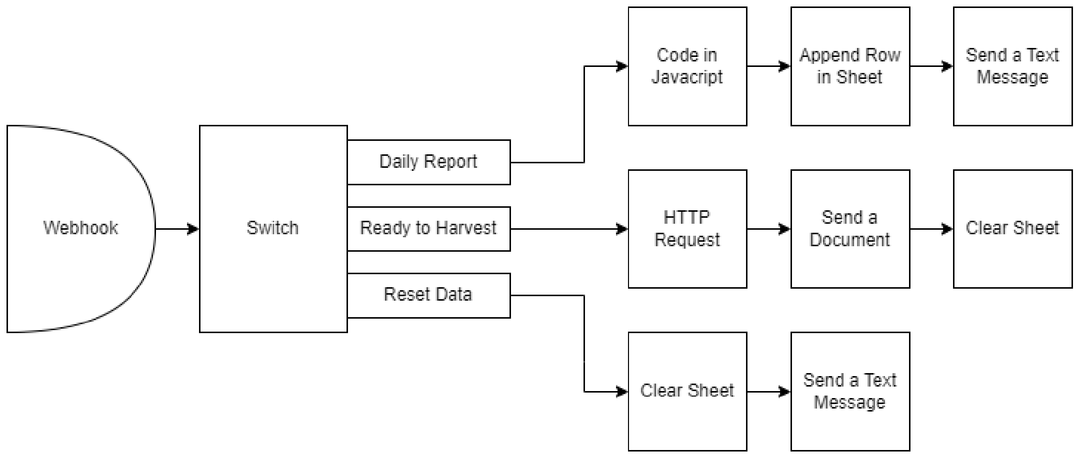

Figure 3. n8n Workflow Architecture

2.5 Sensor Calibration

Sensor calibration was conducted before system deployment to ensure measurement accuracy and operational reliability. The soil moisture sensor was calibrated by observing sensor outputs under dry and wet soil conditions. Based on the calibration results, a threshold value of 1040 was selected as the decision boundary for irrigation control. Sensor readings above the threshold indicated dry soil conditions requiring irrigation, whereas lower values indicated sufficient moisture levels.

The rain sensor was calibrated using dry and wet surface conditions to verify its ability to distinguish rainfall events from normal weather conditions. Calibration results demonstrated consistent detection performance for both environmental states. Peristaltic pump calibration was performed through ten repeated measurements to determine the average water discharge rate. The pump produced an average output of 103.9 mL/min, which was rounded to 104 mL/min for irrigation volume calculations.

2.6 System Evaluation

System performance was evaluated through functional testing, communication testing, and cultivation observations. Functional performance was assessed using a confusion matrix approach by comparing irrigation decisions generated by the system with actual irrigation requirements observed during operation. Four evaluation outcomes were recorded, namely True Positive (TP), True Negative (TN), False Positive (FP), and False Negative (FN). These values were used to calculate Accuracy, Precision, and Recall metrics.

The communication performance of the proposed system was evaluated through end-to-end delay measurements. Delay was defined as the elapsed time between data transmission from the ESP32 and successful reception by cloud services and Telegram notifications.

To evaluate the agricultural effectiveness of the proposed system, pak choy plants were cultivated for 35 days under two irrigation treatments. The first treatment utilized conventional water, while the second treatment employed catfish pond wastewater. Plant growth performance was assessed using three parameters, namely plant height, number of leaves, and harvest weight. The collected data were analyzed to determine the effectiveness of wastewater utilization within the automated irrigation framework.

3.Results and Discussion

3.1 End-to-End Communication Performance

The communication performance of the proposed system was evaluated through end-to-end delay, latency, and throughput measurements. These tests were conducted to assess the effectiveness of data transmission between the ESP32 microcontroller, Telegram Bot, and the n8n automation platform.

3.1.1 End-to-end Delay

The end-to-end delay test measured the transmission time from the ESP32 to Telegram and n8n. The obtained results are presented in Table 2.

Table 2. End-to-end delay measurement

Test	ESP32-Telegram (s)	ESP32-n8n (s)
1	5	11
2	6	11
3	7	12
Average	6.0	11.3

The results indicate that Telegram consistently received data faster than n8n [12], [13]. The average delay from ESP32 to Telegram was 6 seconds, whereas communication through n8n required 11.3 seconds. This difference occurred because Telegram used direct API communication, while n8n required additional webhook processing before data storage and workflow execution.

3.1.2 Latency Performance

Latency testing was performed to determine the response time of the system when receiving commands from Telegram users. Four command scenarios were evaluated, namely /testsiram, /sirammanual, /cekhst, and /resethst.

Table 3. Command latency results

Command	latency (ms)
/testsiram	1.880
/sirammanual	2.019
/cekhst	2.876
/resethst	4.342
AVERAGE	2.779

The average latency of 2.779 seconds indicates that the system can respond to user commands in near real time. The observed latency variation was mainly influenced by Wi-Fi stability and network conditions during communication between Telegram services and the ESP32.

3.1.3 Throughput Performance

Throughput testing evaluated the capability of the system to transmit PDF-based cultivation reports generated through the integrated monitoring platform.

Table 4. Throughput results

Parameter	Value
File Size	47.2 KB
Average Trasmission Time	3.4s
Average Throughput	14.16 KB/s

The average throughput of 14.16 KB/s demonstrates stable communication performance for transferring cultivation reports. Although minor fluctuations were observed during testing, all transmission processes were completed successfully, indicating that the communication infrastructure was sufficient for agricultural monitoring applications[10], [11].

3.2 Irrigation Decision Performance

The reliability of irrigation decisions was evaluated using confusion matrix analysis. The results are presented in **Table 5**. Based on the confusion matrix, the system correctly classified 63 of 70 testing instances. Performance metrics were subsequently calculated and are summarized in Table 6.

Table 5. Confusion matrix results

	Actual Irrigation Required	Actual Irrigation Not Required
Predicted Irrigation	32	4
Predicted No Irrigation	3	31

The obtained accuracy indicates that the proposed irrigation mechanism was capable of making reliable irrigation decisions under varying environmental conditions. The precision value demonstrates that most irrigation actions executed by the system were appropriate, while the recall value confirms the ability of the system to detect irrigation requirements with high sensitivity. These results validate the effectiveness of combining soil moisture sensing, rainfall detection, and growth-stage-based irrigation scheduling within a single decision framework.

Table 6. Classification performance

Metric	Value (%)
Accuracy	90.0
Precision	88.9
Recall	91.4

3.3 Plant Growth Evaluation

Plant growth observations were conducted for 35 days using two irrigation treatments, namely clean water and catfish pond wastewater. Growth performance was evaluated using plant height, leaf count, and harvest weight.

Table 7. Plant growth observation results

Observation Day	Irrigation Type	Height (cm)	Leaves	Harvest Weight (g)
14	Catfish Wastewater	7.5	6	-
14	Clean Water	6.8	4	-
21	Catfish Wastewater	10.3	10	-
21	Clean Water	9.2	6	-
35	Catfish Wastewater	16	20	81
35	Clean Water	14	16	67

The results demonstrate that plants irrigated with catfish pond wastewater consistently exhibited superior growth performance. At harvest time, wastewater-treated plants reached a height of 16 cm and produced 20 leaves with a harvest weight of 81 g. In comparison, plants irrigated using clean water reached only 14 cm in height, produced 16 leaves, and yielded 67 g of harvest weight.

Compared with the clean-water treatment, wastewater irrigation increased plant height by approximately 14.3%, leaf number by 25%, and harvest weight by

20.9%. These findings indicate that the nutrients contained in catfish pond wastewater contributed positively to vegetative growth and biomass accumulation[5].

Figure 4. n8n Workflow Architecture

3.4 Reliability Evaluation

A 24-hour reliability test was conducted to evaluate the stability of sensor operation, wireless connectivity, n8n integration, and irrigation volume consistency. During most observation periods, the system successfully maintained stable Wi-Fi connectivity, accurate sensor readings, and successful communication with Telegram and n8n services. Only one temporary interruption was observed when network disconnection prevented data transmission. After reconnection, synchronization was automatically restored without requiring manual intervention.

The measured irrigation volume remained highly consistent, ranging between 640 mL and 654 mL throughout the testing period. These results demonstrate that the proposed system possesses sufficient operational reliability for continuous smart agriculture deployment.

3.5 Discussion

The obtained results demonstrate that the proposed IoT-based irrigation system successfully integrated irrigation automation, environmental monitoring, and workflow automation into a unified platform. Communication tests confirmed acceptable delay, latency, and throughput values for real-time agricultural monitoring applications. The confusion matrix evaluation further demonstrated reliable irrigation decision-making performance, achieving accuracy, precision, and recall values above 88%.

In addition to technical performance, the plant growth experiment revealed the agricultural benefits of utilizing catfish pond wastewater as an alternative irrigation source. Plants receiving wastewater treatment consistently achieved better growth outcomes than those irrigated using clean water. These findings support the potential of combining IoT automation with aquaculture waste reutilization to improve both cultivation efficiency and environmental sustainability.

Overall, the proposed system demonstrated strong performance from both engineering and agricultural perspectives, indicating its suitability for implementation in sustainable smart farming environments.

4. Conclusion

This study successfully developed and evaluated an Internet of Things (IoT)-based automated irrigation system for pak choy cultivation by integrating an ESP32 microcontroller, soil moisture sensors, a rain sensor, RTC scheduling, Telegram notifications, and n8n workflow automation. The proposed system operated autonomously by performing irrigation decisions based on soil moisture conditions, weather status, and predefined irrigation schedules.

The integration of Telegram and n8n enabled efficient real-time monitoring and automatic data recording, improving operational management and reducing manual intervention. Performance evaluation demonstrated high decision reliability, achieving 90% accuracy, 88.9% precision, and 91% recall in irrigation classification. Communication testing further confirmed stable data transmission between the embedded device and cloud services. In the agricultural experiment, pak choy plants irrigated with catfish pond wastewater achieved superior growth performance compared with conventional water treatment, reaching a plant height of 16 cm, producing 20 leaves, and obtaining a harvest weight of 81 g, whereas the clean-water treatment produced a height of 14 cm, 16 leaves, and a harvest weight of 67 g.

These results indicate that the proposed system is capable of supporting sustainable smart agriculture through reliable irrigation automation and the beneficial reuse of aquaculture wastewater. Future studies may incorporate machine learning techniques to provide adaptive irrigation decisions, evaluate system performance on larger cultivation areas, and conduct economic feasibility analyses to assess long-term operational benefits.

Acknowledgement

Gratitude is extended to all peers, colleagues, and students in the Department of Computer Engineering at Wiralodra University, Indramayu, for all the support provided for this research

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding - No funding information from the authors.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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