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An IoT-Based Smart Fertilization System Using Biofloc Wastewater for Chili Cultivation: A Research-to-Community Innovation in Biofloc Waste Repurposing

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ABSTRACT

Addressing the strategic scope of research, innovation, and knowledge transfer, this study developed an IoT-based smart fertilization system, Smart AgroFlok, which repurposes nutrient-rich biofloc wastewater for precision chili (*Capsicum annuum L.*) cultivation to mitigate agricultural environmental challenges. The technological innovation integrates an ESP32 microcontroller, a soil pH sensor, optocoupler-isolated relays, and automated pumps to drive sustainable resource circularity. System deployment and cross-sector knowledge transfer were executed directly at the Bumi Priangan Forest Farmer Group (KTH Bumi Priangan) in Tanah Laut Regency, Indonesia, empowering local farmers with smart farming capabilities. Employing a quantitative experimental approach, technical evaluation via localized gateway telemetry verified that the automated control logic functions reliably, triggering precision fertigation when soil pH parameters are within the optimal 5.5–6.5 threshold. Network benchmarking revealed a Packet Delivery Ratio (PDR) of 60.4% (183 out of 303 transmitted packets successfully received) due to rural topographic attenuation. Through empirical experimental observations, 10 chili plant samples over a 2-day post-fertilization window demonstrated rapid vegetative responses, with mean plant height increasing from 15.8 cm to 18.6 cm and mean leaf count expanding from 8.4 to 11.4. This research successfully bridges technological innovation and community-driven knowledge transfer for sustainable rural smart agriculture.

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1. INTRODUCTION

The Bumi Priangan Forest Farmers Group in Tanah Laut Regency has implemented the Smart AgroFlok innovation, an Internet of Things (IoT)-based appropriate technology that integrates biofloc aquaculture and crop cultivation to support sustainable agricultural management (Tribun Banjarmasin, 2025). One of the strategic horticultural commodities developed in this system is chili (*Capsicum annuum L.*). Despite its high economic value, chili cultivation productivity is currently still dominated by the use of conventional chemical fertilizers. In the long term, continuous reliance on chemical fertilizers potentially degrades soil quality and disrupts the balance of soil-fertilizing microorganisms (Howe et al., 2024). Given that previous research has predominantly focused on minimizing the impacts of conventional fertilizers, the development of eco-friendly alternative nutrient sources has become highly crucial (Lei et al., 2024).

As a viable solution, wastewater from biofloc fish farming holds significant potential for utilization as liquid fertilizer, as it is rich in macro and micronutrients generated by the activities of nitrogen-compounds-degrading microorganisms (Khanjani et al., 2024; Raza et al., 2024). Nevertheless, manual utilization of this wastewater is frequently suboptimal due to inaccurate dosing, improper application timing, and fluctuations in water pH values, which severely affect the effectiveness of nutrient absorption by plant roots. To overcome these technical constraints, IoT technology within the smart farming framework offers real-time monitoring and automated fertilization solutions. Through the integration of pH sensors and automated actuator systems, the quality of biofloc wastewater can be continuously monitored to ensure a more precise and efficient fertilization process (Al Mamun et al., 2024).

Although the Smart AgroFlok system has been constructed and deployed at KTH Bumi Priangan, its integrated technical performance requires systematic field evaluation. Therefore, this study focuses on evaluating the implementation and integration performance of the Smart AgroFlok system, including the reliability of the soil pH sensing, LoRa-based telemetry, and automated relay–pump control chain. Plant height and leaf count are recorded as short-term observational indicators following system operation, rather than as evidence of the causal effectiveness of biofloc wastewater as a fertilizer. This research does not include laboratory chemical analysis of biofloc wastewater or a controlled comparison with other fertilizer treatments. Accordingly, the primary contribution of the study is positioned as the integration and field implementation of a sensor-driven IoT fertigation system that repurposes biofloc wastewater in a real community farming environment, with plant observations serving as supporting implementation evidence.

2. METHODOLOGY

This study employs a quantitative experimental approach to evaluate the technical implementation and integrated performance of the Smart AgroFlok system. A quantitative approach was selected because the research analyzes numerical data from soil pH measurements, communication logs, automated actuation tests, and supporting chili plant observations. The experimental design actively tests the integrated components—specifically the ESP32 microcontroller, LoRa telemetry module, relay–contactor circuits, and biofloc wastewater delivery mechanism. This framework aligns with the primary objective of assessing whether the sensing, communication, decision-making, and actuation subsystems operate as an integrated IoT fertigation system under field conditions. Changes in plant height and leaf count are interpreted descriptively as short-term observations after system operation and are not used to establish fertilizer effectiveness or causal agronomic superiority. Consequently, the experimental evidence is directed primarily toward validating system integration and implementation rather than proving the fertilizing efficacy of biofloc wastewater.

2.1. Research Gap

Although synthetic chemical fertilizers remain widely used to maintain agricultural productivity, their continuous application can contribute to long-term soil and environmental degradation (Howe et al., 2024; Mansoor et al., 2025; Khatun et al., 2023; Krauss et al., 2025). In response, recent studies on chili cultivation have explored alternative cultivation and nutrient-management practices, including aerated drip irrigation, organic amendments, and phosphorus fertilization (Lei et al., 2024; Ahmad et al., 2026; Hapsoh et al., 2024; Bouras et al., 2024). However, these studies mainly examine crop or nutrient-management outcomes and do not address the technical integration of aquaculture-derived wastewater into an automate fertigation infrastructure.

At the same time, studies on Biofloc Technology (BFT) emphasize its role in managing aquaculture waste and producing nutrient-rich biomass or effluent with potential for resource recovery and circular utilization (Raza et al., 2024; Iber et al., 2023; McCusker et al., 2023; Khanjani et al., 2024; Grytsenko et al., 2025; Mousa et al., 2025). Yet, this body of literature primarily focuses on aquaculture performance, biofloc management, and sustainability, rather than on the field implementation of biofloc wastewater as a controlled input within an integrated crop-production system.

In parallel, IoT and smart-automation studies have advanced real-time sensing, wireless communication, and automated control for precision agriculture and biofloc monitoring (El-Zaher et al., 2025; Al Mamun et al., 2024; Saha et al., 2025; Mansoor et al., 2025; Abid et al., 2024; Shahab et al., 2025). However, these systems generally monitor either agricultural variables or aquaculture conditions separately, while the integration of biofloc wastewater reuse, soil sensing, wireless telemetry, automated actuation, and field deployment in a community farming setting remains insufficiently documented.

Based on this synthesis, the research gap is not primarily the absence of evidence that biofloc wastewater can function as a fertilizer. Rather, the gap lies in the limited implementation evidence for an end-to-end IoT architecture that connects biofloc wastewater recovery with soil-based sensing, LoRa communication, automated relay–pump actuation, and real-world fertigation operation. Therefore, this study contributes by designing, deploying, and evaluating Smart AgroFlok as an integrated system at KTH Bumi Priangan. The contribution is assessed through technical integration and operational evidence, including telemetry performance and automated control functionality, while short-term plant observations are treated as supporting evidence of system operation rather than definitive proof of fertilizer effectiveness.

2.2. Internet of Things (IoT)

The Internet of Things (IoT) is a technology that enables devices to connect to one another via the internet to automatically collect, transmit and process data. According to Al Mamun et al. (2024), the IoT is capable of supporting real-time monitoring and control of biofloc systems. In this study, the IoT was used to connect pH sensors, an ESP32, relays and pumps within the Smart AgroFlok system.

2.2.1 Soil pH Classification and Physiological Impacts

Soil pH levels directly dictate the physiological development of chili plants by altering nutrient availability and root structures. Under highly acidic conditions with a pH < 4.5, plants suffer from structural root damage, restricted vegetative growth, and suppressed water-use efficiency (Ahmad et al., 2026). As the pH

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shifts slightly higher but remains acidic within the 4.5 - 5.5 range, essential macronutrients such as phosphorus, calcium, and magnesium become chemically bound, rendering them unavailable for root absorption (Bouras et al., 2024). Conversely, extreme alkalinity at a pH > 8.5 induces severe leaf chlorosis, hardens the growing medium, and causes overall plant stunting (Bouras et al., 2024; Lei et al., 2024). This alkaline stress is initiated at a moderately basic range of pH > 7.5, where nitrogen availability fluctuates, functional microbial activity declines, and the volatilization of ammonia restricts iron and manganese uptake necessary for chlorophyll synthesis (Lei et al., 2024).To mitigate these physiological constraints, maintaining an optimal soil environment is imperative. Physiological responses are significantly stimulated and organic nutrient absorption is maximized within the ideal, slightly acidic to neutral range of 5.5 - 6.5 (Bouras et al., 2024; Hapsoh et al., 2024). Consequently, this specific optimal range serves as the standard reference baseline to ensure the biofloc wastewater quality matches the natural requirements of the plants.

2.2.2 Hardware Architecture and Sensor Specifications

The hardware architecture of the Smart AgroFlok fertigation subsystem integrates five main components to enable automated pH-based liquid fertilization: a microcontroller unit, a pH sensing module, a signal-conditioning module, a relay-contactor actuation chain, and a pump unit. The system is controlled by an ESP32 microcontroller (ESP32-WROOM-32 based development board), a dual-core processing platform that handles sensor data acquisition, IoT connectivity, and actuator control logic. The ESP32 continuously samples pH readings from the soil medium where the chili plants are cultivated and transmits the data to the cloud-based monitoring platform in real time.

pH measurements are carried out using an analogue pH sensor fitted with a DMS (Data Measurement System) signal conditioning module and a probe installed in the soil where the chilli plants are growing. The DMS module processes the raw electrochemical signal from the probe into a stable analogue voltage, which is then read by the ESP32 via its ADC (Analogue-to-Digital Converter) pin and converted into a pH value using a calibration equation. To conserve power, the DMS module is only activated during the measurement cycle via a power line controlled by the GPIO.

Actuation of the fertilization process is handled by a relay-contactor chain. A single-channel 5V DC relay module with optocoupler isolation receives a low-voltage control signal from the ESP32 and, in turn, drives a Schneider TeSys Deca LC1D09M7 magnetic contactor, which switches the high-power AC circuit supplying the pump. This staged relay-contactor configuration allows the low-power microcontroller to safely control a high-current AC load without direct electrical exposure. The pump unit is an AC 220V booster pump rated at 350W (750W input power) that draws nutrient-rich wastewater from the biofloc holding tank and delivers it through the distribution line to the chili plants. The activation of this pump is dynamically triggered whenever the soil pH sensor detects that the planting medium falls below the optimal threshold required for nutrient absorption. Power for the actuation subsystem is supplied through the site's existing photovoltaic power infrastructure at KTH Bumi Priangan, via an AC inverter. Sensor data and actuator status are transmitted to a cloud-based IoT monitoring platform, enabling real-time visualization of pH values and automated fertigation events for subsequent performance evaluation.

2.2.3 Data Transmission Protocols and Cloud Integration

The communication subsystem of Smart AgroFlok is responsible for transferring pH sensor readings and actuator status data from the ESP32 microcontroller to the cloud-based monitoring platform in real time. Data transmission follows a hybrid wireless topology. First, the soil pH sensor measurements are transmitted from the remote sensing node to the central gateway via a 433 MHz LoRa link. Second, the central gateway utilizes its built-in Wi-Fi module (IEEE 802.11 b/g/n, 2.4 GHz) to establish a persistent internet connection and forward the aggregated data to the cloud network, enabling a persistent internet connection without requiring additional communication hardware. This approach aligns with the broader trend of leveraging low-cost, Wi-Fi-enabled microcontrollers for cloud-integrated precision agriculture systems (Mansoor et al., 2025).

Cloud integration is implemented through the Blynk.io IoT platform, which consists of three interconnected components: an application layer providing a mobile and web dashboard, a server layer functioning as a cloud broker, and a library layer embedded within the device firmware. Communication between the ESP32 and the Blynk server is handled through virtual pins, an abstraction mechanism that decouples the physical pins of the microcontroller from the widgets displayed on the dashboard. Through this mechanism, pH readings acquired by the ESP32 are pushed to the cloud server, processed, and rendered on the Blynk dashboard as a real-time chart, while control commands issued from the dashboard, such as manual pump activation, are relayed back to the relay-contactor actuation chain described in Section 2.2.2.

To ensure uninterrupted data logging, the system operates under Blynk's free-tier service, which imposes a monthly message quota. The transmission interval and payload size were configured to remain within this quota while still preserving near real-time monitoring capability, since exceeding the limit would cause data transmission to be temporarily suspended until the following billing cycle. This cloud-based architecture enables continuous remote monitoring of soil pH levels in chilli plants, as well as automated fertilisation, without the need for farmers to be present on site to supervise the process.

2.3 Smart AgroFlok System Architecture

The Smart AgroFlok system integrates biofloc aquaculture and chili cultivation through an automated fertilization mechanism. Biofloc wastewater generated from fish cultivation is stored in a reservoir, while the soil parameters of the chili plants are continuously monitored using a pH sensor connected to the ESP32 microcontroller. The collected data are transmitted to a cloud platform for real-time monitoring.

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When the wastewater quality meets the predefined threshold, relay modules activate water pumps to distribute nutrient-rich biofloc wastewater to chili plants automatically. This approach improves fertilization efficiency, reduces fertilizer waste, and promotes sustainable agricultural practices through the utilization of aquaculture waste.

2.3.1 Hardware Integration and Wiring Diagram

To provide a clear understanding of the proposed system architecture, the electrical interconnections among the sensing, communication, control, and power subsystems are illustrated in the hardware wiring diagram (Figure 1). The architecture consists of a remote sensing node, a central gateway, actuator modules, and a dual-rail power distribution network designed for reliable operation in an IoT-based biofloc fertigation system.

At the remote sensing node, the analog soil pH sensor is connected to the ESP32 LoRa32 (SX1278) through a dedicated signal conditioning board. Since a pH electrode produces a high-impedance bipolar analog signal, the conditioning circuit performs impedance buffering and voltage level shifting before the signal is acquired by the Analog-to-Digital Converter (ADC) of the ESP32. In this study, the sensor calibration and functional threshold triggering were verified through controlled localized testing to ensure precise relay activation before field deployment.

The measured pH data are transmitted wirelessly to the central gateway using LoRa communication operating at 433 MHz. The LoRa-based architecture enables long-range, low-power communication, making it suitable for distributed agricultural monitoring applications where the sensing unit is located remotely from the control station.

At the gateway, the ESP32 LoRa32 receives sensor data and controls the actuator subsystem through optocoupler-isolated relay modules. The controlled actuators include a DC water pump, a biofloc fertilizer solenoid valve, a solar power contactor, and a generator contactor. The optocoupler provides galvanic isolation between the low-voltage control circuit and the 12 V inductive loads, thereby minimizing electrical interference and protecting the microcontroller from switching transients and back-electromotive force (back-EMF) generated during actuator operation.

The proposed system employs a dual-rail power architecture consisting of regulated 5 VDC and 12 VDC supply lines. Electrical energy generated by the photovoltaic panel is managed through a solar charge controller and stored in a 12 V battery. The 12 V rail directly supplies the electromechanical actuators, while a DC–DC buck converter provides a regulated 5 V supply for the ESP32 controllers, the pH sensing circuit, and the relay logic. Although different voltage levels are used, all electronic modules share a common ground reference to maintain signal integrity and stable system operation.

Overall, the hardware integration combines sensing, wireless communication, actuator control, and renewable power management into a unified architecture suitable for autonomous biofloc fertigation. The separation between the low-voltage control circuitry and the high-power actuator subsystem, together with optocoupler isolation and a dual-rail power distribution scheme, enhances electrical reliability, operational safety, and long-term stability in outdoor agricultural environments.

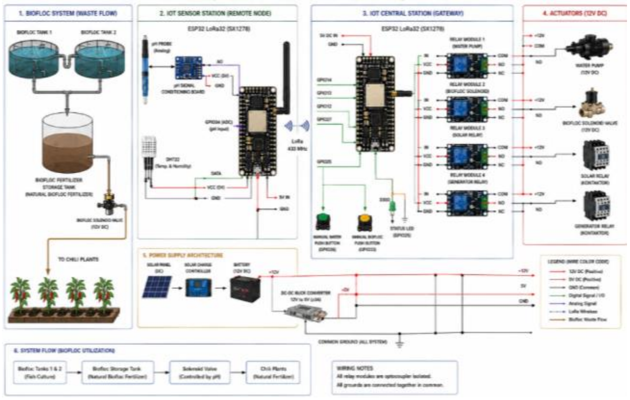

Figure 1. Hardware wiring diagram of the proposed IoT–LoRa based biofloc fertigation system

2.3.2 System Operational Logic and Flowchart

The operational algorithm of the proposed IoT–LoRa based biofloc fertigation system is illustrated in Figure 2. After power-up, the ESP32 gateway initializes the LoRa SX1278 transceiver, relay modules, network interface, and cloud communication services before entering a continuous monitoring loop.

During operation, the gateway receives pH measurements transmitted from the remote sensing node through the LoRa communication link operating at 433 MHz. Each incoming packet is validated using a format and integrity checking procedure before the pH value is extracted and stored. Valid measurements are subsequently uploaded to the cloud dashboard for real-time monitoring.

The control logic then determines whether the system is operating in automatic or manual mode. In manual mode, the controller waits for user commands from the Blynk application or local push buttons and executes the selected relay operation. In automatic mode, the received pH value is compared with the predefined control thresholds used for biofloc fertilizer management.

When the soil pH value is detected within the optimal growth range of 5.5–6.5, the controller triggers the precise fertigation cycle by activating the water pump relay and the biofloc solenoid valve to maximize nutrient absorption by the roots. Conversely, if the soil pH deviates into extreme stress zones, the automated dosing is suspended to prevent nutrient lock-off or root damage. The operation is maintained for a controlled dosing period and then the actuators are deactivated automatically. If the soil pH value remains stable and does not trigger the fertilization threshold, the controller maintains the current actuator state without modification.

The sensing, communication, decision-making, and actuator control stages are executed repeatedly in a cyclic manner, enabling continuous monitoring and autonomous fertigation control. This closed-loop operational strategy ensures that pH measurements received from the remote node are continuously evaluated and translated into appropriate control actions while

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maintaining synchronization between the gateway, actuator subsystem, and cloud monitoring platform.

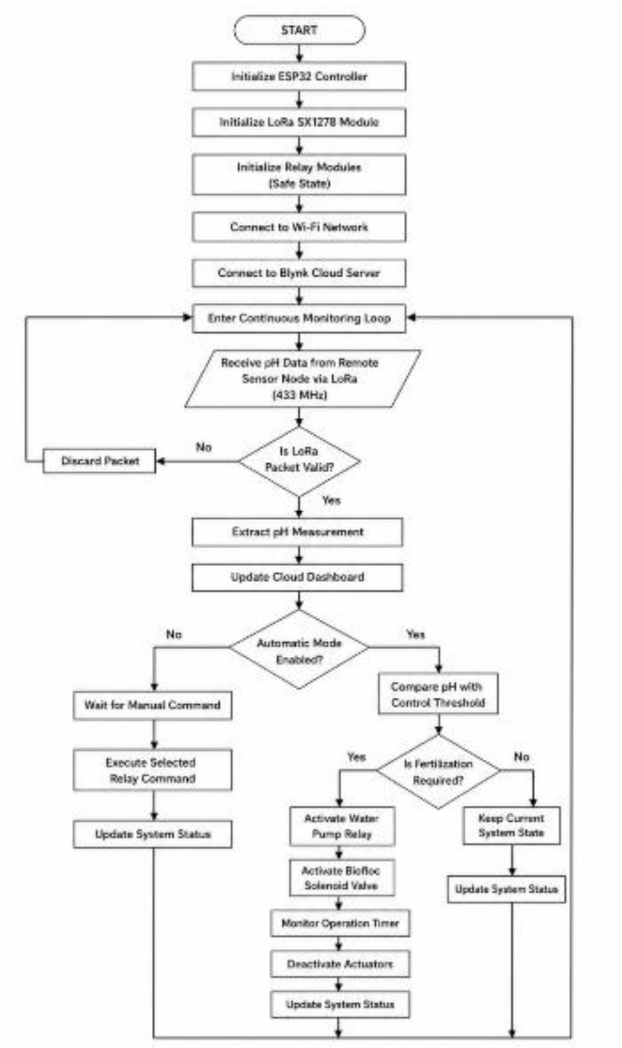

Figure 2. The system operational logic and flowchart algorithm of the proposed IoT–LoRa based biofloc fertigation system.

2.4 Types and Sources of Data

This study utilized both primary and secondary data sources. Primary data were obtained directly from the Smart AgroFlok system deployed at KTH Bumi Priangan, Tanah Laut Regency. These data consisted of pH sensor measurements, IoT communication logs, and chili plant growth parameters, including plant height (cm) and leaf count. Secondary data were collected from scientific journals, conference proceedings, books, and relevant literature related to biofloc technology, Internet of Things (IoT), smart farming, and sustainable agriculture.

2.5 Data Collection Procedure

Data collection was focused on two primary aspects: system integration functionality and agronomic plant responses. The automatic fertilization system was designed to activate based on the soil pH threshold parameters [5.5–6.5] to maintain an optimal growing environment. Due to ongoing field technical maintenance of the continuous remote data logging infrastructure during the evaluation period, the real-time soil pH fluctuations were monitored via localized hardware debugging rather than continuous cloud logs. Meanwhile, empirical observations of chili plant growth parameters specifically plant height and leaf count were recorded systematically over the observation period as supporting evidence of system operation and field implementation.

2.6 Data Analysis

The collected data were analyzed using descriptive quantitative methods. The hardware integration performance was evaluated by assessing the functional reliability of the soil pH sensor triggers and the subsequent relay-contactor activation sequence during localized system testing. Meanwhile, agronomic responses of the chili plants were analyzed by comparing the initial and final empirical measurements of plant height and leaf count. The synthesized results were then interpreted to evaluate the overall technical performance and field implementation of the Smart AgroFlok system in supporting automated biofloc wastewater utilization for chili cultivation.

3. RESULTS AND DISCUSSION

3.1 IoT Communication Performance

The technical evaluation of the Smart AgroFlok system was carried out by validating the functional integration and local wireless communication performance between the remote soil pH sensing node and the central ESP32 gateway. While continuous cloud-based data logging was suspended due to localized technical maintenance on the remote server infrastructure, the core data acquisition loop and low-power wide-area network (LPWAN) topology were fully verified through direct telemetry logging at the local gateway.

Wireless transmission reliability was assessed by analyzing the Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR) of the 433 MHz LoRa link under actual field operating conditions. A representative sample of the local telemetry data logged by the gateway is presented in Table 1, confirming continuous sub-GHz radio frequency data synchronization.

Table 1. Local LoRa telemetry network performance logged at the central gateway.

Time	Seq	Src	RSSI	SNR	Quality
19:41:28	292	0x10	-93	8.5	Adequate
19:41:37	293	0x10	-92	9.0	Adequate
19:41:58	296	0x10	-93	8.5	Adequate
19:42:27	297	0x10	-93	8.3	Adequate
19:42:58	298	0x10	-93	8.5	Adequate
19:43:27	299	0x10	-93	8.8	Adequate
19:43:58	300	0x10	-93	8.5	Adequate
19:44:27	301	0x10	-93	8.5	Adequate
19:44:58	302	0x10	-93	8.3	Adequate
19:45:12	303	0x10	-92	8.8	Adequate

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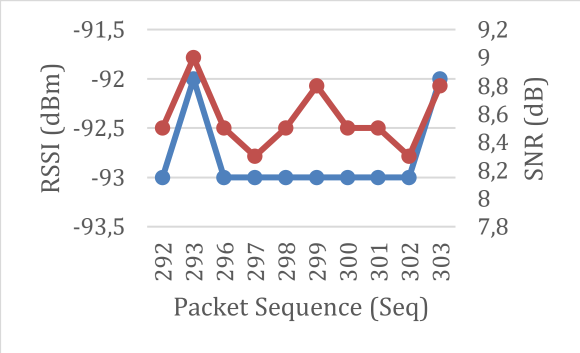

Figure 3. Graphical visualization of RSSI and SNR signal performance across LoRa packet sequences.

As evaluated in Table 1, the data packet sequence numbers (Seq 292 to 303) demonstrate the localized data transmission from the sensor node (0x10). The hardware network achieved highly stable link characteristics, with the RSSI consistently holding between -92 dBm and -93 dBm. Despite the highland agricultural topography that typically introduces signal attenuation, these RSSI levels are highly adequate for robust sub-GHz RF propagation. Furthermore, the SNR values remained robustly positive, fluctuating tightly between 8.3 dB and 9.0 dB. This indicates that the LoRa SX1278 transceiver effectively isolated the incoming soil pH data from background electromagnetic noise.

To fully evaluate the long-term reliability of this sub-GHz telemetry transmission, a network throughput analysis was conducted during the field trial. Out of 303 total data packets transmitted by the soil pH sensor node, 183 packets were successfully received and logged by the gateway infrastructure, resulting in a Packet Delivery Ratio (PDR) of 60.4%. The observed packet loss of 39.6% is primarily influenced by several specific environmental and physical factors characteristic of the KTH Bumi Priangan highland farming site: (1) undulating topography and uneven soil contours that disrupt direct Line-of-Sight (LoS) propagation between the remote sensor node and the central gateway, leading to multi-path fading; (2) dense vegetation, including chili plant canopies and surrounding undergrowth, which induce absorption and scattering of 433 MHz radio frequency waves due to high foliar moisture; and (3) localized electromagnetic interference (EMI) originating from nearby photovoltaic power infrastructure, specifically solar inverters and DC-DC converters, which induce background noise during transmission bursts. Although the network efficiency requires further optimization through directional antennae or adaptive spreading factors, the 183 successfully logged packets provided a statistically sufficient and continuous dataset to validate the system's automated control logic during the evaluation window.

Concurrently, the operational logic was verified via localized hardware debugging using an Arduino IDE serial interface and a digital multimeter, as illustrated in Figure 1. The hardware trials confirmed that the central gateway accurately processed the incoming soil pH frames. Whenever the received soil parameters were validated within the target fertilization threshold (5.5–6.5), the GPIO pins successfully executed the control sequence, triggering the optocoupler-isolated relays to actuate the 12V DC biofloc solenoid valve and the AC booster pump. Consequently, the technical evaluation proves that the local sensing, wireless telemetry, and automatic actuation chains are entirely reliable and fully operational.

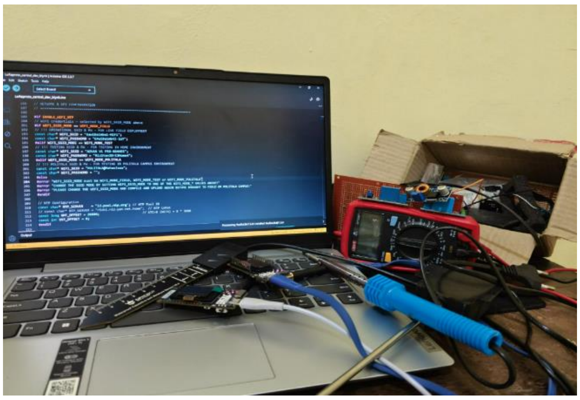

Figure 4. Setup for localized hardware debugging and operational logic verification of the IoT gateway.

3.2 Impact of Automated Biofloc Fertilization on Chili Growth

Short-term plant observations were conducted on 10 chili plant samples over a 2-day post-fertilization window to document plant conditions following operation of the automated biofloc wastewater delivery system. These observations were intended as supporting implementation evidence and were not designed as a controlled efficacy test of biofloc wastewater as a fertilizer because the study did not include a control group, fertilizer comparison, or chemical nutrient analysis. Plant height and leaf count before and after the observation window are summarized descriptively in Table 2.

Table 2. Growth performance of 10 chili plant samples over a 2-day biofloc application.

Sample	Init. H (cm)	Final H (cm)	Init. Leaves	Final Leaves
1	15	16	6	7
2	11	13	8	11
3	22	26	11	11
4	15	16	4	10
5	19	23	8	19
6	14	18	11	18
7	16	20	11	10
8	18	22	8	9
9	12	14	9	12
10	16	18	8	11
Mean	15.8	18.6	8.4	11.4

As detailed in Table 2, the recorded observations showed an increase in mean plant height from 15.8 cm to 18.6 cm and an increase in mean leaf count from 8.4 to 11.4 over the 48-hour observation window. These descriptive changes document the condition of the observed plants following automated biofloc wastewater application; however, given the short observation period and the absence of a control or comparison treatment, they should not be interpreted as causal evidence of fertilizer effectiveness.

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Figure 5. Chilli plants before Biofloc fertilisation

Figure 6. Chilli plants two days after biofloc fertilisation

The observed short-term changes provide supporting field evidence that the integrated system was able to deliver biofloc wastewater to the cultivation area and that the monitored plants continued to exhibit vegetative changes during the observation window. However, the present design does not allow the observed changes to be attributed solely to the nutrient content of the biofloc wastewater or to be used as proof of superior agronomic efficacy. Because no laboratory nutrient analysis, control group, or comparative fertilizer treatment was included, the agronomic observations are interpreted cautiously as complementary evidence to the primary technical findings. Future studies should use longer observation periods, controlled treatments, and nutrient characterization to evaluate fertilizer effectiveness separately.

4. CONSLUSION

This study demonstrated the implementation and field evaluation of the Smart AgroFlok system as an integrated IoT-based biofloc wastewater fertigation system at KTH Bumi Priangan, Indonesia. The primary contribution of the study lies in integrating soil pH sensing, ESP32-based processing, sub-GHz LoRa telemetry, automated relay–pump actuation, and biofloc wastewater reuse within a single operational architecture and deploying it in a community farming environment. Technical and network evaluations showed that the integrated system could acquire sensor data, transmit telemetry, and execute automated control actions under field conditions. The system recorded RSSI values ranging from -92 dBm to -93 dBm and positive SNR values, while a throughput test produced a Packet Delivery Ratio (PDR) of 60.4% (183 of 303 transmitted packets successfully received). Although packet loss of 39.6% indicates a clear need for communication optimization, the received telemetry supported verification of the sensing–communication–actuation workflow during the evaluation period.

The 2-day observations of 10 chili plants recorded increases in mean plant height from 15.8 cm to 18.6 cm and mean leaf count from 8.4 to 11.4. These observations are reported as supporting implementation evidence and should not be interpreted as definitive proof of the fertilizing effectiveness of biofloc wastewater because the study did not include a control group, comparative treatment, or nutrient-content analysis. Overall, the study advances research-to-community innovation by demonstrating how aquaculture wastewater reuse can be operationalized through an integrated smart-farming system for rural implementation. Future work should improve telemetry reliability through antenna and communication-parameter optimization, restore continuous cloud synchronization, and separately evaluate agronomic effectiveness using longer-term controlled experiments and wastewater nutrient characterization.

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