Energy-Efficient IoT Green House Solution for Real-Time pH Control

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***Abstract*— Maintaining optimal irrigation water pH is essential for plant health and soil sustainability but is often neglected in conventional systems. This paper proposes a low cost, automated solution using a PID controlled system that integrates multiple water and chemical tanks with real-time sensor feedback. Irrigation volume is tailored using plant age and environmental data from Firebase. An analog pH sensor and the JXBS-3001-PH-RS ensure accurate pH regulation and validation. Excess water is reused to minimize waste. Communication is achieved via an ESP-NOW mesh network and a LoRaWAN gateway, delivering precise, energy-efficient control for precision agriculture.**

Keywords— PID control, ESP-now, LoRAWAN, Power Optimization

I. Introduction

As sustainable agriculture gains importance, maintaining the chemical quality of irrigation water especially pH has become as vital as managing its quantity. This project introduces a smart, automated greenhouse system that regulates irrigation water pH in real time using a PID controller. The system dynamically adjusts water composition based on soil moisture and pH data from calibrated sensors, while crop-specific requirements are retrieved from a cloud-based database. To enhance resource efficiency, it incorporates a rainwater-prioritized reuse mechanism. Communication is managed through ESP-NOW and LoRaWAN, enabling low-power operation ideal for long-term use in remote agricultural settings.

II. Lietrature Review

Extensive research has focused on improving agricultural productivity and sustainability through technology. Precision agriculture, which leverages data and automation for tasks like controlled irrigation, fertilization, and real-time monitoring, has emerged as a key approach to maximizing yields while minimizing resource use.

Bell pepper (Capsicum annuum L.), a nutritionally and economically important crop [4], benefits from smart cultivation practices. Flores-Velazquez et al. [5] show that structured stem training improves yield. However, inefficiencies remain in water management, pH regulation, and irrigation scheduling [6]. Traditional systems using one or two tanks limit adaptability [7], while newer approaches advocate multi-tank setups integrating rainwater, tap water, and supply tanks for optimized water use [8], [9].

Proper irrigation timing is essential for crops like bell pepper, which progress through distinct growth stages. Studies by Krause et al. [10] and Pepper Geek [11] highlight stage-specific water needs, supporting adaptive irrigation strategies. Additionally, since many pH control systems lack precision [6], [12], this study implements an algorithmic pH regulation method to ensure accurate nutrient availability and optimal plant health [3].

For communication and energy management, Irga and Rahayu [13] highlight the high-power consumption of traditional Wi-Fi-based microcontrollers in remote settings and recommend energy-efficient strategies like deep sleep and task scheduling. Similarly, Maurya et al. [14] explore LoRaWAN's long-range, low-power potential, noting its effectiveness but also pointing out trade-offs in latency and energy use when relay nodes are involved.

To bridge existing gaps, the Power Green system integrates ESP-NOW for low-power internal communication and LoRaWAN for long-range transmission. By transmitting data only at set intervals or during critical events and leveraging the ESP32's dual-core processing with deep sleep functionality, power consumption drops significantly from 624 mW to just 4.1 mW. This aligns with Laha et al. [15], who emphasize the value of responsive, low-power IoT systems for real-time soil monitoring and irrigation. Collectively, these efforts highlight the synergy between agronomic science and embedded systems in creating sustainable, adaptive agricultural solutions.

A. Research Gap

The Bellpepper - Power Green project features a smart water reuse system that minimizes water and chemical consumption by storing and recalibrating treated water between irrigation cycles. It prioritizes rainwater, applies tap water only when needed, and uses automated pH adjustments for optimal growing conditions [16]. Overall, the system combines advanced sensors, PID-based pH regulation, and low-power communication via ESP-NOW and LoRaWAN, all integrated through Firebase, to deliver a scalable, sustainable solution for precision agriculture.

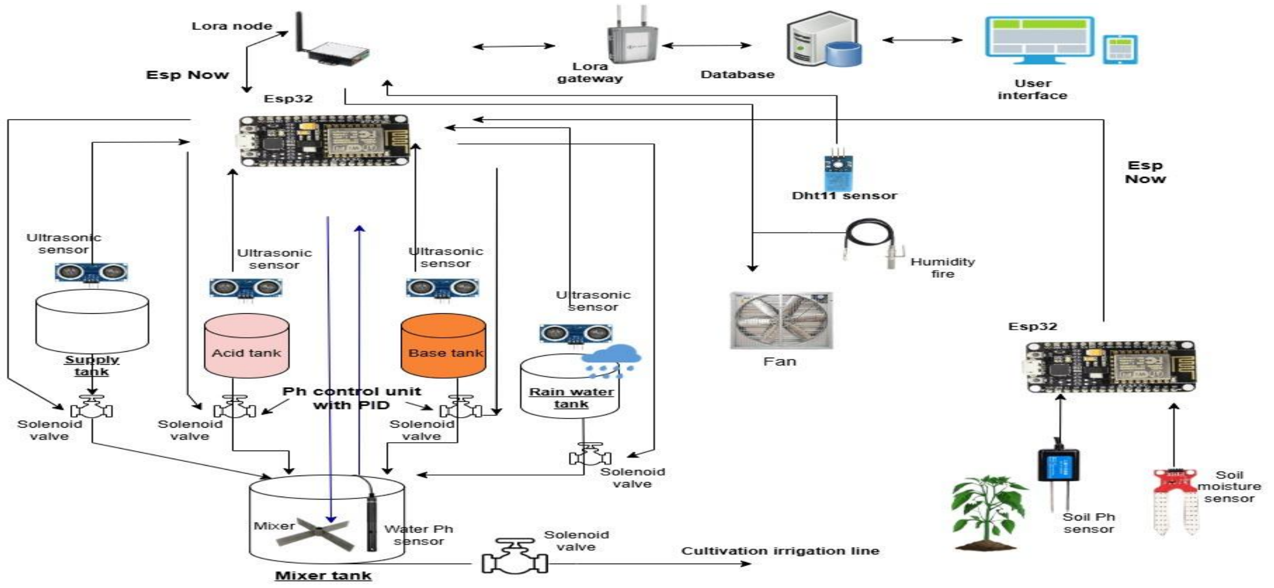

Fig. 1. Overall system diagram.

III. SYSTEM OVERVIEW

The proposed system integrates sensor-based monitoring, automated pH regulation, and intelligent water management into a unified control unit. By leveraging both hardware and software components, the system dynamically adjusts water quality in real time, ensuring optimal conditions for soil application while minimizing waste and enhancing operational efficiency.

A. pH Regulation System

The system employs high-sensitivity sensors to continuously monitor soil pH and moisture, using crop specific data from Firebase to calculate the exact irrigation volume and ideal pH. It dispenses only the required amount of pH-adjusted water, storing any excess for future use. A PID controller ensures precise pH regulation in the mixing tank by iteratively adjusting acid or base dosing based on the real-time error between measured and target pH levels, enabling stable and accurate correction.

B. Efficient Usage of Water

The system optimizes water usage by accurately estimating irrigation needs based on soil moisture and crop-specific data from the cloud. It releases only the necessary amount of water, while any excess treated water is stored and reused in future cycles by blending with fresh sources. This method conserves water, reduces chemical use, and enhances overall efficiency and sustainability.

C. Power Optimized Network for IoT

The system uses a multi-tier communication architecture to ensure efficient data exchange. Within the greenhouse, sensor nodes communicate via an ESP-NOW mesh network, allowing fast, peer-to-peer data transfer without Wi-Fi. A central gateway then transmits this data using a low-power LoRaWAN link to an external office network, which forwards it to Firebase for cloud storage and analysis. This design enables reliable, real-time monitoring and control while minimizing energy usage.

IV. METHODOLOGY

A. IoT Integration in Smart pH Regulation System

IoT integration is key to automating the smart pH regulation system, enabling real-time monitoring, control, and remote management. An ESP32 microcontroller serves as the central unit, interfacing with two sensors: the JXBS-3001-PH-RS (for soil pH and moisture) and an analog pH sensor (for water in the mixing tank). These continuously provide analog data, which is digitized and processed in real time.

1) Cloud-Based Decision Support: A Firebase cloud database stores historical and crop-specific data such as:

- Target pH values by crop stage
- Soil-specific moisture thresholds
- Water needs based on plant age and environment

At each cycle, the system uploads sensor readings and retrieves crop-specific targets from Firebase to determine:

- The required pH level
- The irrigation volume

This cloud-based model allows dynamic adjustments and easy scalability by simply updating the database.

2) Data Flow and Communication: The data flow is structured as follows:

1) **Sensor Data Collection:** Soil moisture and pH sensors send real-time data to the ESP32 microcontroller.
2) **Cloud Upload:** The microcontroller uploads this data to the Firebase cloud database
3) **Parameter Retrieval:** Based on the uploaded data, Firebase returns target irrigation parameters such as ideal pH and required water volume tailored to the crop and environmental conditions.
4) **PID Control:** The microcontroller applies PID logic using the retrieved targets to calculate the necessary adjustments.
5) **Actuation:** The system activates dosing pumps to add acid or base and controls irrigation based on the calculations.

6) **Feedback Logging:** Final pH and water usage data are sent back to Firebase for logging and analysis.

B. ID-Based pH Regulation Mechanism

Achieving accurate pH regulation for soil application requires a responsive control system capable of handling nonlinear chemical reactions and environmental variations. The proposed solution addresses this using a closed-loop Proportional–Integral–Derivative (PID) control algorithm that precisely manages the mixing of acidic and basic agents in the tank to reach the desired pH level [17], [18]. This process involves control logic, chemical interactions, mixing behavior, and iterative feedback correction to ensure stable and accurate pH adjustment.

1) Control Objective and Rationale: Directly calculating the required quantity of acid or base to reach a specific pH is not straightforward due to:

- **Nonlinear pH behavior** caused by logarithmic [H+] concentration [18].
- **Chemical buffering effects** in natural water [17].
- **Time delay** in reaching equilibrium after chemical addition [17].

Due to these complexities, attempting a single-shot correction often leads to **overcorrection or undershooting** the target pH [18]. To overcome this, a **feedback mechanism** is used where the **pH error** is computed and minimized iteratively through **proportional, integral, and derivative** adjustments [17].

2) PID Control Logic: Let:

- pH_{set}: target pH value calculated from soil pH and plant data.
- $pH_{current}$: measured pH in the mixing tank.
- $e(t) = pH_{set} - pH_{current}$: error signal.

The PID controller generates a control signal *u(t)* (volume of acid/base to be added) using the formula:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)\, d\tau + K_d \cdot \frac{de(t)}{dt}$$

Where:

- K_p: proportional gain, addresses current error.
- K_i: integral gain, addresses accumulated past error.
- K_d: derivative gain, predicts future error based on rate of change.

The output u(t) determines the volume and direction of chemical adjustment:

- f $e(t) > 0$: add acid to lower pH.
- If $e(t) < 0$: add base to increase pH.

3) Chemical Agents and Reactions: To adjust the pH, the system uses **citric acid ($C_6H_8O_7$)** and **sodium bicarbonate ($NaHCO_3$)** [19] due to their safety, solubility, and suitability for agriculture. These are stored in separate acid and base tanks and dispensed via **peristaltic pumps**.

Acid reaction (to decrease pH):

$$C_6H_8O_7 \rightarrow 3H^+ + C_6H_5O_7^{3-}$$

Base reaction (to increase pH):

$$NaHCO_3 + H^+ \rightarrow Na^+ + CO_2 + H_2O$$

4) Mixing Process and Feedback Loop: The mixing tank receives water either from a rainwater tank or the tap water line, depending on availability. After computing the required irrigation volume (based on soil moisture, plant age, and conditions fetched from a Firebase database), the system fills the tank with this amount.

Once filled:

1) The **initial pH** is measured.
2) PID calculates required corrective action.
3) Acid or base is added accordingly.
4) **Mixing delay** (e.g., 10–15 sec) allows for uniform distribution and settling.
5) **pH** is re-measured.
6) Steps 2–5 are repeated until the error is within a (e.g., $\Delta pH \leqslant 0.05$).

C. Water Reusage Mechanism in Smart pH Regulation

A standout feature of the smart pH regulation system is its ability to reuse treated water between irrigation cycles, significantly reducing water and chemical usage. After each cycle, any remaining pH-adjusted water is stored. In the next cycle, the system evaluates the required irrigation volume using soil and crop data from Firebase. If the stored water meets the volume requirement, its pH is rechecked and fine-tuned. If additional water is needed, it is supplemented with rainwater or tap water.

1) Intelligent Mixing and Re-Calibration: The reused water enters the system already conditioned, minimizing further pH adjustment. The PID controller re-measures its pH and fine tunes the dosing of acid ($C_6H_8O_7$) or base ($NaHCO_3$) to ensure accurate regulation.

The following control logic is used in this mixed source.

1) Measure current residual volume and pH in mixing tank
2) Calculate the total required volume for the next cycle
3) Add supplemental water (rain or tap) to reach the required volume
4) Measure the new pH of the diluted mixture
5) Use PID loop to correct the pH if needed

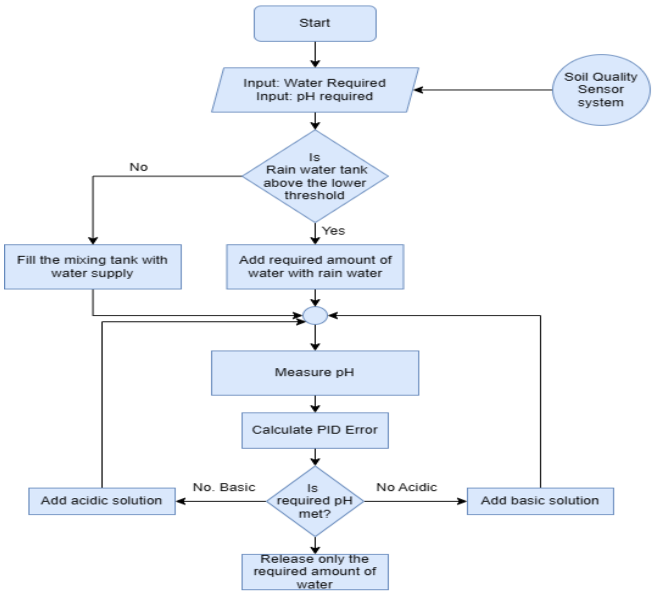

Fig. 2. Mixing tank diagram.

This method introduces a form of incremental dosing, minimizing chemical waste and reducing stress on the pH regulation algorithm.

2) Benefits of Water Reuse: The reuse mechanism offers several engineering and environmental advantages:

- Water Conservation
- Chemical Optimization
- Time Efficiency
- System Resilience

3) Real-Time Monitoring and Logging: All data on reused water volume, pH values before and after adjustment, and its role in the final mix is logged to Firebase for long-term analysis of water use and reuse efficiency.

4) Cloud-configured thresholds determine reuse suitability based on:

- Water age, Deviation from target pH, Minimum required volume

This transforms the system from simple recycling to a smart, data-driven reuse engine, advancing pH-managed irrigation.

D. Sensor Calibration for Accurate Measurements

1) To ensure precise environmental monitoring, both the standard pH sensor (used in the mixing tank) and the JXBS 3001-PH-RS soil sensor (used in the field) were calibrated [20]. Both sensors output analog voltages proportional to pH or moisture levels and require calibration to accurately convert these signals into real-world measurements.

2) pH Sensor Calibration: Calibration was performed using three standard buffer solutions with known **pH** values: **4.01, 6.89**, and **9.32**. The process involved:

1) Recording analog voltage outputs V1, V2, V3 corresponding to the three buffer solutions.
2) Assuming linear behavior, we calculated the slope and intercepted for the line:

$$pH = m \cdot V + c$$

using:

$$m = \frac{pH_2 - pH_1}{V_2 - V_1}, \quad c = pH_1 - m \cdot V_1$$

3) The third point was used for validation, ensuring the accuracy of the linear fit.

The computed formula was embedded into the firmware
to convert real-time voltage readings to pH values during operation.

3) Moisture Calibration: The JXBS-3001 sensor measures soil moisture as voltage, which was calibrated by testing in soil samples with known moisture levels. A linear or polynomial curve was fitted to relate voltage to volumetric water content (VWC). This calibration enables the microcontroller to convert voltage to VWC in real-time, ensuring accurate pH control, optimized water use, and reliable system performance.

E. Communication Architecture

Facilitation of wireless communication between distributed components inside the greenhouse, the system uses an ESP-NOW based peer-to-peer network. Each node whether a sensor module, actuator, or mobile unit is equipped with an ESP32 microcontroller configured for low-power operation. These nodes transmit and receive packets directly with the central controller using MAC addressing, ensuring minimal latency and energy-efficient operation without requiring a Wi-Fi router or internet connectivity.

This ESP-NOW network allows the system to operate

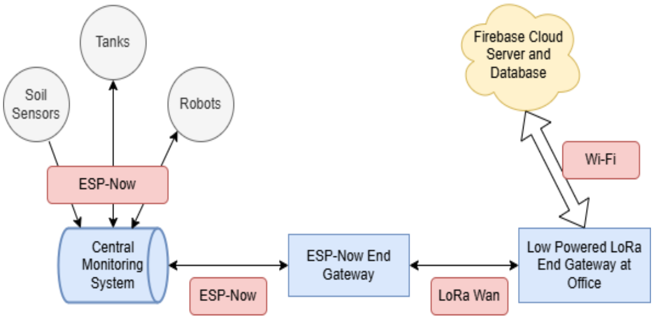

Fig. 3. Overall network diagram

reliably even in remote or bandwidth-limited environments. Once data is collected and processed by the central node, it is relayed to an external office network via a LoRaWAN gateway, which transmits the information to the Firebase cloud platform for storage, analytics, and remote access.

F. Power Optimization for Communication Network

1) Intra-Greenhouse Communication: ESP-NOW, a low-latency, connectionless communication protocol developed for ESP32 microcontrollers, allows direct device-to-device data exchange using MAC addressing. Unlike traditional Wi-Fi networks, ESP-NOW does not require complex handshaking or a router, significantly reducing communication overhead and power usage. Each node transmits its readings or commands periodically or based on predefined triggers to the central controller, enabling efficient real-time control over all systems inside the greenhouse without relying on power-hungry network infrastructure [21].

2) Long-Range Gateway Communication: The gateway link utilizes the long-range, ultra-low-power features of LoRa technology to enable efficient communication over several hundred meters. LoRaWAN transmits compact, structured data packets containing only essential sensor readings and control updates, minimizing payload size and conserving energy. This ensures reliable data transmission from the greenhouse to the cloud, even in areas with limited or no Wi-Fi connectivity. [1], [22].

3) Cloud Integration and Wi-Fi Optimization: To make the system viable for low-power operation, an aggressive power-saving strategy is implemented. Rather than maintaining a persistent Wi-Fi connection, which averages around 624 mW in traditional setups, the ESP32 at the office node is placed in deep sleep mode by default. In this state, it consumes power in the micro-watt range and remains idle until it is either woken by a periodic timer or an interrupt signal.

Every minute, the ESP32 briefly wakes from deep sleep, initiates a Wi-Fi session, pushes or fetches the required data from Firebase, and immediately returns to sleep. This timed wake-and-transmit cycle drastically cuts down the average power consumption to approximately 4.1 mW, representing a significant improvement over always-on Wi-Fi configurations [21].

V. RESULTS AND CALCULATIONS

A. *Regulation of pH with PID*

Mixing chemical agents (acidic or basic) with a PID-based feedback loop mechanism was demonstrated using a prototype, and the tuned control gains Kp, Ki, and Kd exhibited the following behavior. These reactions occur within the mixing tank and are allowed to stabilize before the next measurement.

TABLE I
PID PARAMETER TUNING AND OBSERVED SYSTEM BEHAVIOR

Tuning	Kp	Ki	Kd	System Behavior
Initial Guess	50	0	0	Moderate response
High Kp	110	0	0	Fast Response, Overshoots
Low Kp	20	0	0	Very slow response, barely reaches target
Low Kd	110	0	10	Overshoot Reduced
Increased Kd	110	30	0	Smoother approacht
Increased Ki	110	30	0.1	lead to instability
Optimized Tuning	110	30	0.05	Quick and stable settling

B. *Experimental Setup for Stage-Wise Irrigation*

This research was implemented using two separate bell pepper plants, referred to as Plant A and Plant B, to evaluate the effects of growth stage-based water allocation and real time soil pH regulation.

1) The experiment utilized two different irrigation solutions:

- **Plant A** received non-adjusted water according to the soil PH.
- **Plant B** received pH-adjusted nutrient solution using a real-time PID-controlled acid/base mixture system.
- Morning irrigation: around 8:30 a.m.
- Evening irrigation: around 4:30 p.m.

In this experiment, irrigation volume was tailored to the bell pepper plant's specific growth stage vegetative, flowering, or fruiting allowing dynamic adjustment to ensure optimal water distribution. For Plant B, a real-time soil pH monitoring and control system was implemented using an analog sensor and a PID-controlled acid/base pump to maintain the soil pH around the optimal 6.5 level for bell pepper growth. Both plants were grown under identical greenhouse conditions with the same soil type, light exposure, and container size to ensure environmental consistency.

Plant B, which received stage-specific water volumes and pH-regulated irrigation, exhibited faster and healthier growth with richer leaf color and more uniform development.

Plant A, which received fixed-volume, non-regulated irrigation, showed slower growth and signs of nutrient stress in some weeks due to less optimized pH conditions.

These results support the conclusion that growth stage-based water management, combined with real-time soil pH regulation, significantly enhances plant development and health in bell pepper cultivation.

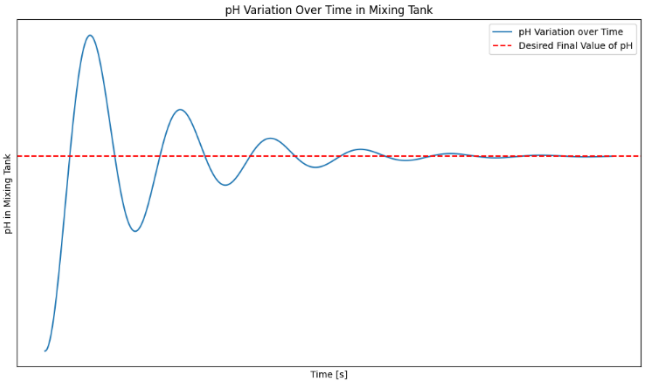

Fig. 4. Settling of pH in mixing tank over time

C. *Results and Power Efficiency Analysis*

The ESP32-based communication framework was evaluated for its energy efficiency in a remote agricultural monitoring context. The system was designed to minimize power usage through scheduled task execution and aggressive utilization of deep sleep modes. By dividing sensor communication and network transmission tasks across the ESP32's two cores and avoiding continuous Wi-Fi operation, the system significantly reduces average current draw.

1) System Operation Profile: The ESP32 wakes up every 60 seconds to perform communication and data processing tasks. During each cycle, it remains active for approximately 50 milliseconds, after which it returns to deep sleep mode. The two cores are utilized concurrently:

- **Core 0:** Handles **ESP-NOW** communication with internal sensor nodes.
- **Core 1:** Manages **LoRaWAN** data transmission, JSON formatting, and sensor interfacing.

This parallel task allocation reduces the total active time per cycle, allowing faster completion of tasks and an earlier return to low-power sleep mode

2) Power Consumption Calculations: To evaluate the energy consumption under this optimized communication scheme, the following parameters are used:

- Battery Capacity: 3200 mAh
- Active Current Consumption: 160 mA
- Sleep Current Consumption: 10 mA
- Cycle Duration: 60 seconds
- Active Time per Cycle: 0.05 seconds
- Sleep Time per Cycle: 59.95 seconds

Energy Consumption per Cycle:

Active: $I_{active} \times t_{active}$ = 160mA × 0.05s = 8mAs
Sleep: $I_{sleep} \times t_{sleep}$ = 10mA × 59.95s = 599.5mAs
Total per cycle: 8 + 599.5 = 607.5mAs

Average Current Draw:

$$I_{avg} = \frac{607.5\,mAs}{60\,s} = 10.125\,mA$$

Estimated Battery Life:

$$T_{life} = \frac{3200\,mAh}{10.125\,mA} \approx 316\,hours \approx 13.2\,days$$

3) Comparative Analysis: For comparison, an always-on ESP32 system operating at a constant 160 mA would consume:

$$T_{life} = \frac{3200\,mAh}{160\,mA} = 20\,hours$$

TABLE II

BATTERY LIFE COMPARISON BETWEEN POWER MODES

Mode	**Avg. Current Draw**	**Estimated Battery Life**
Optimized (Deep Sleep)	10.125 mA	∼13.2 days
Always-On	160 mA	∼20 hours

The Non-Power Optimized device always drew power and fluctuates a bit when transferring data, but the power optimized device only drew power on pre-planned or invoked occasions and power was drawn only in spikes.

Remarks: The power optimization strategy extends battery life by over 15 times without losing responsiveness. It minimizes Wi-Fi use by updating Firebase once per minute and uses LoRaWAN interrupts for urgent transmissions. Combining scheduled wakeups, parallel tasks, and a communication hierarchy (ESP-NOW → LoRaWAN → Wi-Fi) ensures energy efficiency while maintaining full communication, making it a robust low-power solution for long-term precision agriculture deployment.

D. Web Based User Interface

The BellCrop Protector web interface enables real-time monitoring and control of greenhouse conditions throughout the bell pepper growth cycle. It displays key parameters like water demand, target pH, temperature, and humidity, with visual indicators for tank levels and soil data. Built-in controls for fan and water flow support responsive and informed decision-making in precision agriculture.

VI. CONCLUSION

This work presents a smart, energy-efficient irrigation system that advances precision agriculture by combining real-time pH regulation, moisture monitoring, and intelligent water reuse. Using a PID controller with sensor feedback and cloud-based data, it accurately adjusts water volume and pH through controlled dosing of citric acid and sodium bicarbonate. The integration of ESP-NOW and LoRaWAN ensures low-power, reliable communication, while cloud connectivity enables adaptive, remote decision-making. Experimental results confirm its effectiveness in optimizing resource use and supporting sustainable, scalable agricultural practices.

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