

A Wireless Sensor Network (WSN) Application for Smart Monitoring and Control System for Drought

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Abstract— *The Philippine government persistently grapples with the challenges of low crop yield caused by drought, requiring efficient water management strategies. This becomes increasingly critical given the rising population and decreasing food supply. This study introduces an innovative precision agriculture system powered by the Internet of Things (IoT), designed to address this issue. This IoT-enabled system harnesses wireless technology, connecting environmental and soil sensors via a Wireless Sensor Network (WSN). These sensors provide real-time data on farmland stress conditions, enabling farmers to respond swiftly with appropriate interventions. The gathered data are stored in both local and remote database systems and relayed via WiFi to an automated device—a programmable circuit attached to a magnetic latch solenoid—to control field irrigation. The system was piloted in three 12x16 m² plots in San Ramon, Zamboanga City, employing 24 sensor and automation boxes strategically deployed across the irrigation network. Each box, protected by a robust, 3D-printed ABS plastic casing, safeguards the intricate circuitry from harsh environmental conditions. MQTT and HTTP protocols facilitate the delivery of information to a dedicated Android Application, ensuring remote access. The data is further analyzed using a Neural Network model, optimizing the irrigation schedule intelligently. Our findings validate the efficacy of this smart farming system as a scalable and efficient solution for precision agriculture.*

Keywords— WSN, Drought, Neural Networks, Precision Agriculture, IoT

I. INTRODUCTION

By 2045, the Philippine population is projected to burgeon to 142 million, per the 2010 Census-based population projections [1], accentuating the pressing concern of adequate food availability. Traditional farming methodologies currently practiced pose a considerable challenge in ensuring optimal crop care and monitoring. Technological aids that could alleviate these challenges are scarcely available to Filipino farmers, and their exorbitant costs make them largely inaccessible. Furthermore, data gathering, crucial for agricultural research, analytics, and development, is still a laborious and time-consuming process, resulting in limited and difficult access to valuable data for improved farming strategies.

As the Philippines grapples with the impacts of El Niño, drought has emerged as a predominant concern for farmers, severely affecting crop growth, survival, and yield due to elevated temperature levels [2].

Numerous research groups have been striving towards smart agriculture solutions, contributing to the body of knowledge in this area. Water, an indispensable resource in farming, and its efficient usage has been a focal point for innovation, especially considering that the food and agriculture sector is the most significant consumer of water resources, a hundred times more than personal use [3]. With around 70% of water sourced from rivers and groundwater, nearly half of the 3600 km³ of freshwater is lost through evaporation and crop transpiration. Hence, managing the supply and demand of groundwater, a vital resource for irrigation, livestock, and drinking water stored in underground aquifers, poses a formidable challenge for communities worldwide.

For agriculturists seeking innovative water management solutions, Wireless Sensor Network (WSN) technology might provide the answer. The recent advancements in WSN technology facilitate environmental data monitoring regardless of geographical location [4]. Current implementations involve measuring data using sparsely located sensors. Besides supporting environmental stewardship, WSN can offer financial benefits to

farmers and ranchers by easing compliance with state and federal water regulations. IoT technology, networks, and data collection could help farmers reduce water consumption by up to 25% [5].

The role of water usage laws becomes particularly significant during drought seasons. Several studies have proposed optimized water usage solutions using WSN powered by solar power [6], mobile-integrated and IoT-based smart irrigation systems [7], low-cost irrigation monitoring, and control systems [8], among others. A survey on WSN in agriculture showed an overview of a ZigBee based network application to farming, monitoring ambient, soil, and plant conditions [10].

The integration of Precision Agriculture (PA) and IoT for data collection and decision making has been explored [11], alongside the use of neural networks and Evapotranspiration (ET) based methods [12], and Machine Learning for decision support systems in water management [13]. This paper, however, puts a spotlight on Neural Network (NN), which mimics the human brain's data processing, offering a solution for irrigation decisions.

Parameters such as ambient temperature, humidity, and soil moisture, typically observed in fuzzy logic-based irrigation systems, don't correlate significantly with crop needs. However, they can be effectively utilized for irrigation decisions via a neural network. This technology, therefore, is the focus of this paper, with Filipino farmers being one of the primary target users.

The current paper presents an intelligent crop monitoring and automated irrigation system with three specific objectives:

- Integration of sensors into a central system to collect environmental and soil data, transmitting the data to the cloud via MQTT.
- Design and installation of robust, weather-resistant enclosures for the circuitry.
- Calculation of the irrigation schedule for an entire season, automatically controlling irrigation based on NN predictions.

The proposed system is capable of monitoring in-field conditions, recognizing crop heat stress via soil and environmental sensors, and conveniently displaying the statuses on a mobile app. It sends commands to automation boxes to initiate irrigation when specific thresholds are met. All relevant information is stored for historical reference and future analysis. By automating irrigation at critical crop growth phases, effective water resource utilization can be achieved, mitigating the negative impacts of various environmental stresses [14].

The subsequent sections of this paper are organized as follows: Section 2 presents the system deployment, Section 3 discusses the results of the modular systems, and finally, Section 4 concludes the paper, followed by the references.

II. SYSTEM ANALYSIS AND DESIGN

A. Theoretical Framework

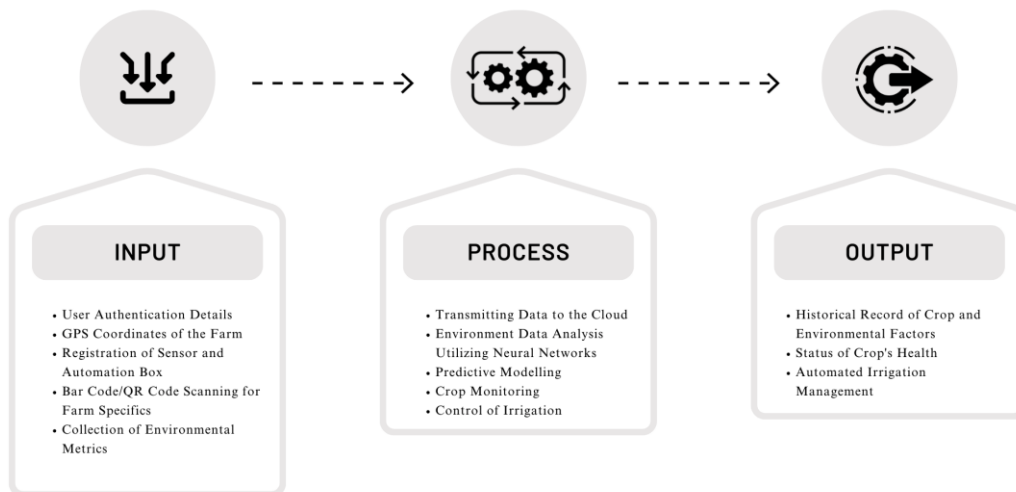


Fig. 2.1 Theoretical Framework

The proposed theoretical framework for our study is categorized into three distinct sections: Input, Process, and Output. The 'Input' stage entails collecting various data including user authentication details, the farm's GPS coordinates, registration details of the sensor and automation box, and farm specifics through bar code or QR code scanning. Additionally, it involves recording environmental metrics like ambient temperature, humidity, light intensity, precipitation, wind direction, soil moisture, soil temperature, and pH. Next, the 'Process' stage involves transferring these collected data to the cloud, analyzing environmental data using neural networks, developing a predictive model, monitoring crop health, and controlling irrigation based on the analysis. Finally, in the 'Output' stage, the system generates a historical record of crop and environmental parameters, updates on the health status of the crop, and provides an automated irrigation management system. The entire framework forms a comprehensive system to enhance agricultural productivity using modern technologies and data analysis techniques.

B. Systems Architecture

The system architecture of this study, as shown in Fig.2.2, basically consists of a (1) Sensor box, (2) Automation Box, (3) Central Device, (4) Gateway, (5) IoT Platform, and (6) Client. The system is discussed based on the three main functions of the project, namely: Monitoring of the Environmental Stress of the Crops, Analyzing and Processing of data collected, and Automatic Control of the Irrigation flow.

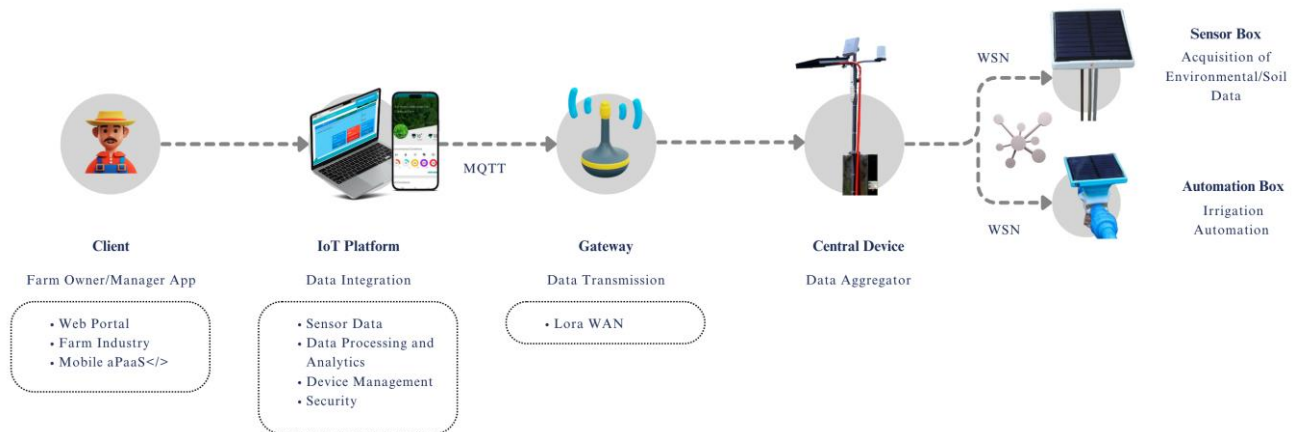


Figure 2.2 Prototype Installation of the Proposed System

- 1) **Sensor Box.** This box is integrated with soil temperature, soil moisture, and Ph sensors to collect data for soil conditions of the crops. Sensor data are acquired simultaneously by the ESP8266 and are connected through mesh networking. The implementation of these boxes offers a low cost and reliable multipurpose solution for collecting data over a sparsely deployed field. [16]
- 2) **Automation Box.** The automation box serves to allow the flow of irrigation once triggered by an HTTP request from the IoT Platform finally decided through NN.
- 3) **Central device.** This device gathers the information from the sensor boxes and also measure other environmental parameters such as ambient temperature, humidity, luminosity, rainfall, and wind direction. The central device also manages some of the immediate data processing tasks and gives the command to the Automation box for irrigation. Once the internet connection is limited, data will be placed temporarily in the local database. Once the internet is available, the data stored locally will update the online database. The data gathered and preprocessed will be sent to the local gateway where an internet connection is possible.
- 4) **Gateway.** The gateway uses LoRa WAN, which is a communication system used to receive and send the data forwarded by the Central device to the nearest cellular base station where internet connection is found. This technology can transmit data wirelessly up to 15 km [17] and consumes a minimal amount of power, which offers scalability of the system [18]. Beforehand the researchers did a test benchmark in the actual deployment of what technology to use as a medium of communication. Table 2.1 shows the dominance of the LoRa RF Module for this application.

Module	Expected Result	Actual Result	Remarks
Wi-Fi Module	30 m	More than 50m	Passed
Lora RF Module	1 km	More than 1 km	Passed

Table 2.1 Gateway Communication Technology Benchmarking.

- 5) **IoT Platform.** In this portion, data integration is done on the cloud where management and processing of sensor data for analysis are being done with security. The platform allows showing the status of all connected sensors and automation boxes, such as the battery levels, signal strength, and location. The proponents used CloudMQTT. MQTT is considered since it is a very light messaging protocol to use with embedded systems, sensors, and mobile applications [19]. The platform aid in the development of the app instead of spending time scaling the broker or patching the platform.
- 6) **Client.** This refers to the farmer’s application that can be used on either web and mobile platform or in the farm industry monitoring and control system. The mobile app is programmed in Android while the web portal is programmed using Php Laravel.

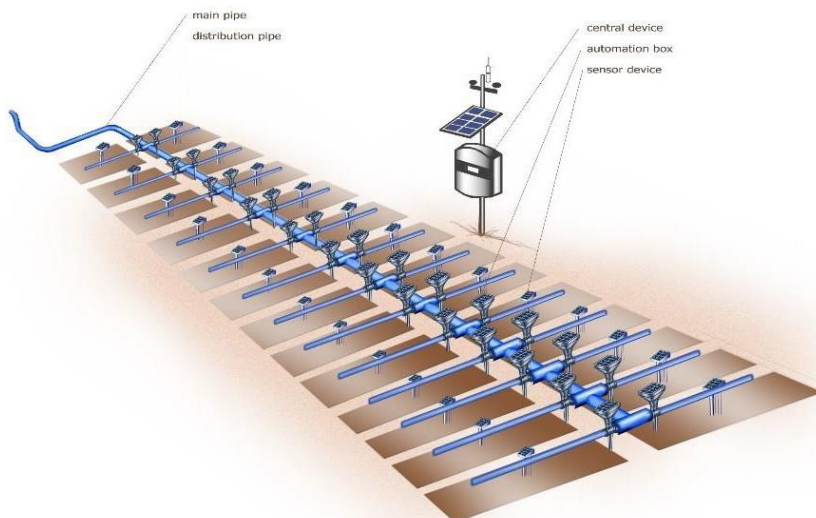


Figure 2.3 Prototype Installation of the Proposed System

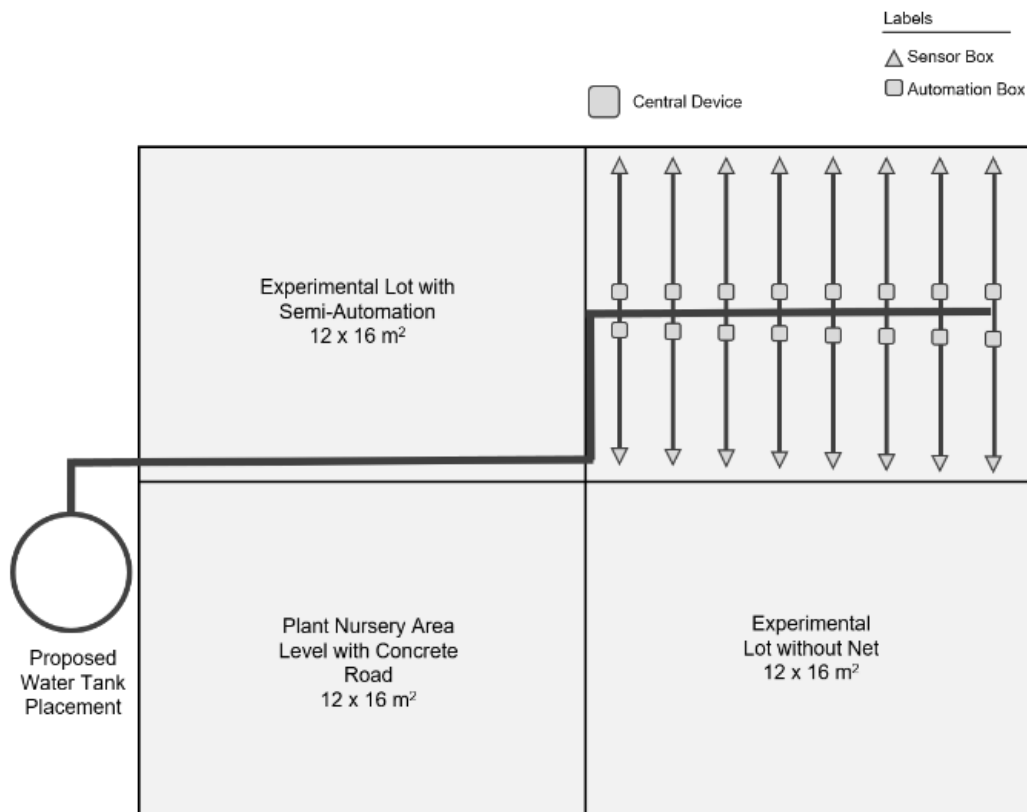


Figure 2.4 600 sq.-meter experimental lot

C. *System Flowchart*

The system flowchart shown in Figure 3.1 outlines how the Sensor box provides soil data (Soil Moisture, Soil Temperature, and pH) from the sensors. This data is digitized and stored in a local database, then forwarded to the central device for further processing and analysis.

The Central Device (CD) also collects environmental parameters and soil parameters from the sensor boxes. These parameters are used to compute irrigation requirements. The device controls the sensor and makes irrigation decisions. The central device initially operates in admin mode, where the farmer provides farm details and other relevant data for calculations.

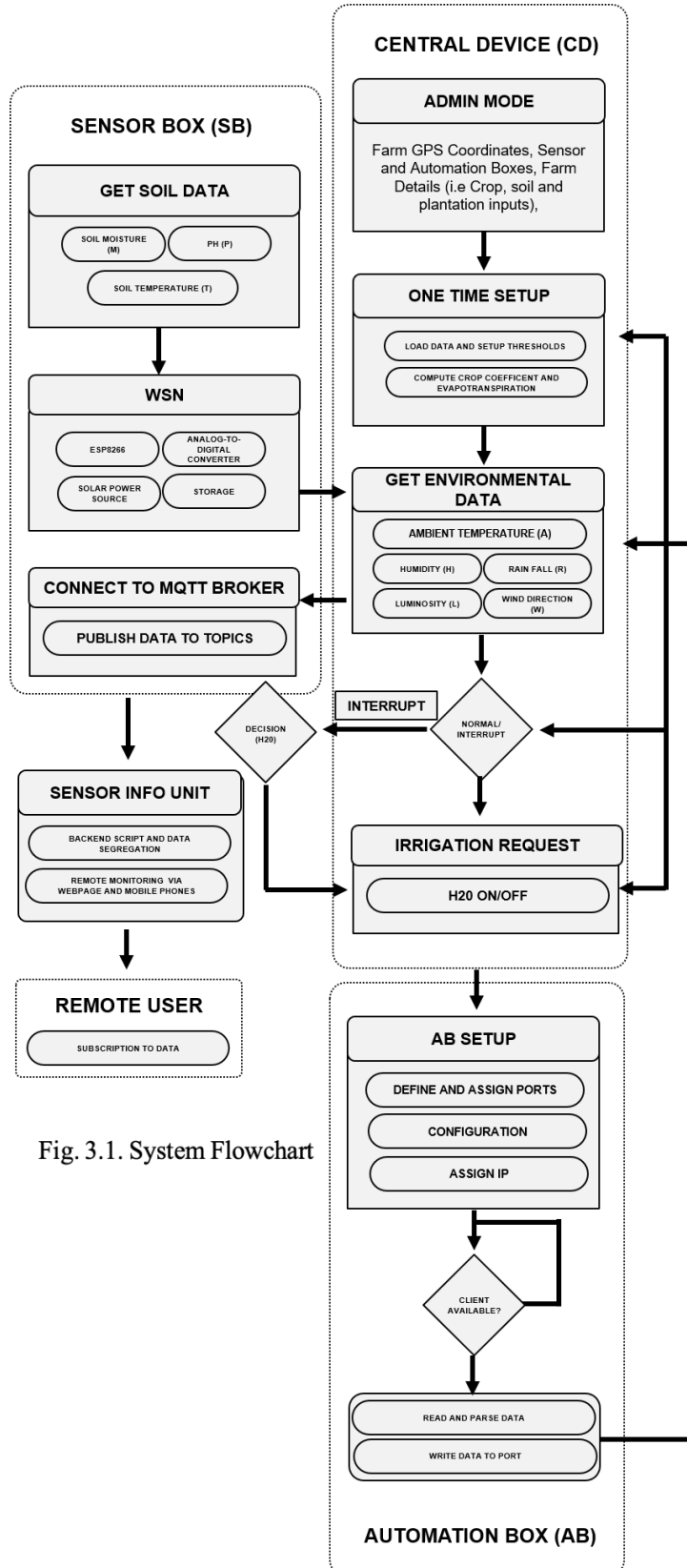


Fig. 3.1. System Flowchart

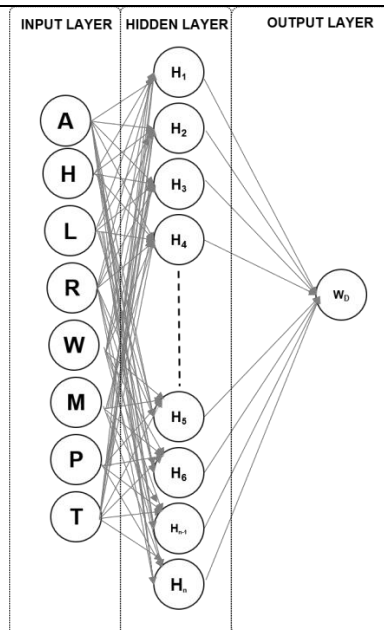


Fig. 3.2. 2-Layer Neural Network

The central device employs a two-layer neural network, depicted in Fig. 3.2, for making decisions. This structure consists of an input layer, a single hidden layer, and an output layer. The input layer accepts normalized values of environmental and soil parameters, as well as the time of day. These inputs are then processed in the hidden layer using an activation function. The output layer, employing a sigmoid activation function, subsequently provides a binary output determining whether irrigation is required or not.

D. Data Flow Diagram

The data flow diagram, depicted in Fig. 3.3, elucidates the movement of data within the proposed smart irrigation system. The flow commences with the sensor box, which gathers soil data and environmental parameters. This information is subsequently processed by the central device. The processed data is then transmitted to the cloud for comprehensive analysis. Notifications are dispatched to the farmer's mobile application based on this data. In response to these notifications, the farmer can undertake any necessary actions.

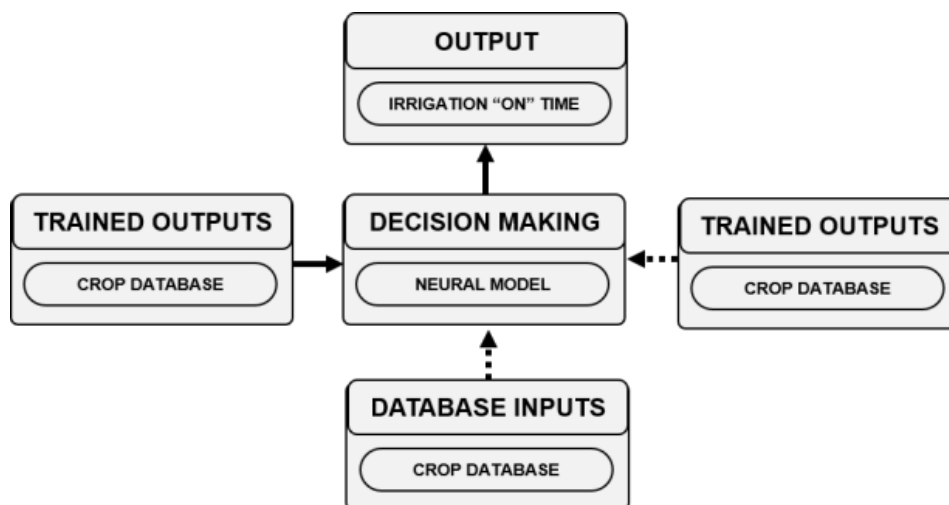


Fig. 3.3 Data Flow Diagram

Upon the completion of the initial setup, data is gathered from the sensors at specified intervals and subsequently, decisions are made once an adequate amount of data is accumulated. Given the frequent fluctuations in weather conditions, the system operates in two modes, necessitating the selection of the appropriate mode. The system typically functions with initial values calculated during the setup phase, while the alternative mode is invoked under adverse conditions.

As illustrated in Figure 3.2, a 2-layer Neural Network (NN) is trained using the "nftool" function in MATLAB. The decision block of the Central Device, shown in Figure 3.1, deploys this NN. The system employs the learned weights, biases, and inputs to generate a final decision (n=8). This decision is then communicated to the automation box, which activates the corresponding areas. Figure 3.3 demonstrates the inputs, expected outputs, and outputs obtained through training. The initial training is facilitated by using production data, physical data, crop stage information, and pre-saved outputs from the database. The current data operates the trained network to derive the desired output.

Subsequently, the Central Device connects to the MQTT broker, operational on the Sensor Info Unit, via the internet, uploading the sensor data for additional analysis and real-time remote observation. The Central Device-MQTT creates a virtual connection with the broker and delivers data to pertinent topics. This data can be accessed remotely by subscribing to specific topics. A paid platform, CloudMQTT, which implements the protocol, is used to create the broker.

Algorithm 1

- | | |
|---|--|
| <p>1: Inputs: Crop, Date of Crop Plantation, Coordinates</p> <p>2: Output: Irrigation Request based on Neural Network</p> <p>3: During setup:</p> <p>4: In admin mode:</p> <p>5: Select Crops based on Date of Crop Plantation & Area at Coordinates</p> <p>6: End admin mode</p> <p>7: Load Stressor Thresholds</p> <p>8: Compute Crop Coefficient and Evapotranspiration</p> <p>9: Estimate Irrigation schedule</p> | <p>10: Upload schedule to Cloud</p> <p>11: End setup</p> <p>12: Outside setup:</p> <p>13: Read Environmental and Soil Parameters</p> <p>14: Connect and send data using MQTT</p> <p>15: Mode selection: Normal Mode or Adaptive Mode</p> <p>16: If Normal Mode:</p> <p>17: Send to Iterative User: irrigation computed using Evapotranspiration (ET)</p> |
|---|--|

The automation box operates based on HTTP requests received from the central device. The pseudocode in Algorithm 2 represents the operations of the Automation Box, which encompasses:

- (a) A controller rooted in the ESP8266, designed to accept, process requests, and emit signals to
- (b) A relay that oversees the operation of the
- (c) Solenoid valve.

During the setup phase, ports are allocated to distinct regions within the field and set as outputs to manage the water flow via the solenoid valve. A static IP address is assigned to the automation box to allow easier detection by the central device. This device then transmits requests to particular unique identifiers to control irrigation in specific sectors of the field.

Algorithm 2

- | | |
|---|---|
| <ul style="list-style-type: none"> 1: Require: a unique identifier, Irrigation Trigger 2: During setup: 3: Define port mode 4: Assign ports 5: Configure Automation Box 6: Assign static IP 7: End setup | <ul style="list-style-type: none"> 8: For the client: 9: Read incoming data 10: Parse data into identifier ID, Irrigation Trigger 11: Write to port 12: Repeat from 9 13: End client 14: End algorithm |
|---|---|

E. Software and Hardware Requirements

Software Requirements:

ESP8266/ESP32 Firmware Programming: Arduino IDE
 IoT Platform: Cloud MQTT
 Database Management: MySQL
 Application Development: Android Studio for the mobile app, PHP Laravel for the web portal.

Hardware Requirements:

Sensor box: ESP8266 microcontroller, Soil Moisture Sensor, Soil Temperature Sensor, Soil pH Sensor, Battery, Solar Panel.
 Automation box: ESP8266 microcontroller, Solenoid Valve, Battery, Solar Panel.
 Central Device: Raspberry Pi 4, Battery, Solar Panel.
 Gateway: Raspberry Pi 4 with LoRa HAT, Battery, Solar Panel.

F. System Development and Testing

The proposed smart irrigation system will be developed using the waterfall model, starting with requirements analysis, then system design, implementation, integration, testing, and finally, maintenance. The system will be tested in a controlled environment before field testing in a 600 square meter experimental lot.

The development and testing phase will consist of unit testing, integration testing, system testing, and acceptance testing. Any bugs identified during testing will be documented and resolved. Once the system passes all tests, it will be ready for deployment.

G. System Deployment and Maintenance

Upon successful completion of the testing phase, the system will be deployed in the designated agricultural fields. The deployment will involve installing sensor boxes, the automation box, the central device, and the gateway in strategic locations across the field. An initial calibration and configuration process will be carried out to ensure that all components are functioning correctly and communicating efficiently.

Once deployed, the system will enter a period of continuous monitoring and maintenance. This maintenance includes regular checks and calibrations of sensors, hardware inspections, and routine software updates. During this maintenance period, user feedback will also be collected to refine the system and implement enhancements, if necessary.

Furthermore, periodic training sessions will be provided to the farmers or users, guiding them on how to interpret the data, act upon the notifications, and manage the system effectively. A dedicated support team will also be set up to address any issues faced by the users and provide necessary assistance.

H. System Evaluation

System evaluation will be an ongoing process throughout the lifecycle of the smart irrigation system. Key performance indicators (KPIs) will be identified and measured regularly to assess the system's effectiveness and efficiency.

Some of these KPIs could include:

- 1.) Accuracy of the prediction model: This is evaluated by comparing the predicted irrigation timings with actual needed timings.
- 2.) System reliability: These measures how often the system encounters errors or fails.
- 3.) User satisfaction: Conducting surveys or interviews with the farmers or users will gauge their satisfaction levels and their overall experience with the system.
- 4.) Crop yield: A comparison of crop yield before and after the deployment of the system will be a direct measure of the system's impact.

The results of the evaluation will feed back into the system design and development process, informing improvements and refinements. It is essential to ensure that the system continues to meet the evolving needs of the users and the agricultural industry.

III. RESULTS AND DISCUSSIONS

In this section, the researcher intends to present and explain the results obtained from designing and developing this study.

- 1.) *Assemble incorporated transducers and embed them into the main system that will gather the environmental and soil data and send these data to the cloud via MQTT.* This data was then transmitted to the cloud through MQTT. Prior to the final fabrication of the PCB board, three prototype iterations were developed. The use of surface-mount device (SMD) components facilitated a miniaturization process, resulting in a final production board that was 23% smaller than the preceding prototype. The latest version of both sensor and automation circuitry boards are depicted in Figure 3.2.

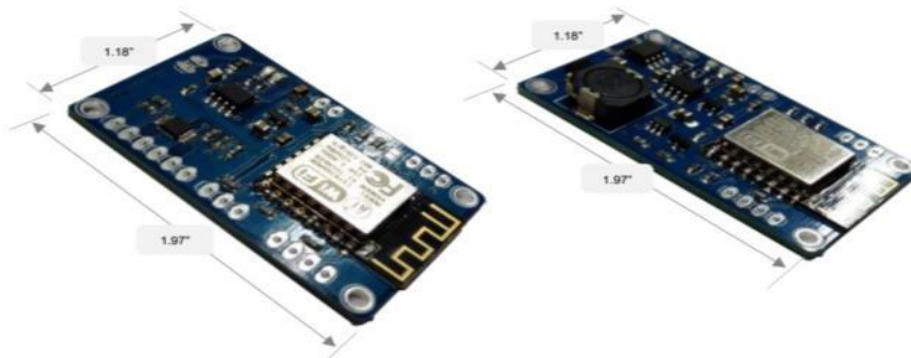


Figure 3.2 Sensor Box (Left) and Automation Box (Right) Circuitry, Prototype Final Version.

Equipped with soil temperature, soil moisture, and pH sensors, these final boards are powered by a 2200mAh battery and housed within bespoke 3D printed enclosures. Metallic rods, crafted from copper, serve dual purposes as conductors for the electrical signals emanating from the soil and as supports when implanted into the soil. The lengths of these rods are standardized to ensure accurate sensor readings. To withstand the pressure exerted during insertion, the rods must maintain a secure contact with the enclosure. A silicon sealant is applied at this junction to not only fortify adherence between the rod and the enclosure but also to reduce risks associated with long-term exposure to moisture, such as water seepage into the gaskets.

The final setup integrates environmental sensors into the central device. The device, featuring a capacitive touch LCD screen, provides a user-friendly interface for farmers to interact with the environmental and soil data of their crops. Information regarding active sensors and automation boxes, along with their registered serial numbers, is also displayed on this screen as shown in Figure 3.3.

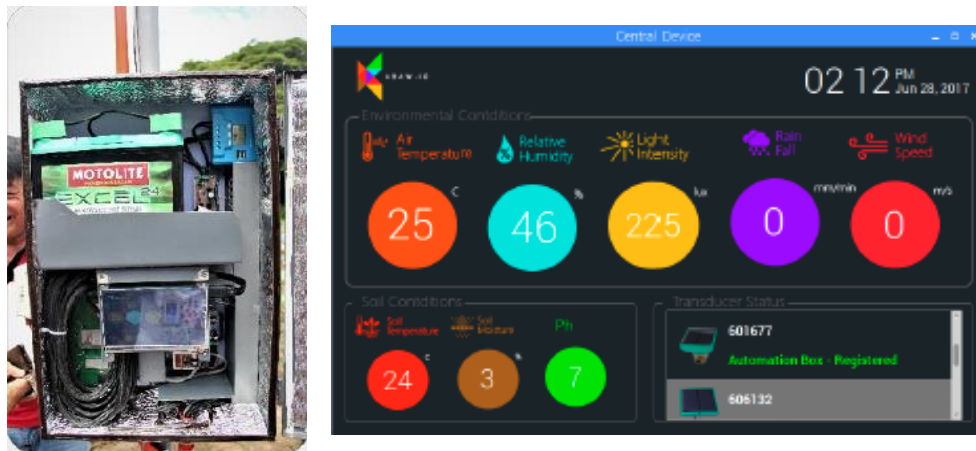


Figure 3.3 Central Device with the Sensors and LCD screen along with the readings from the sensors.

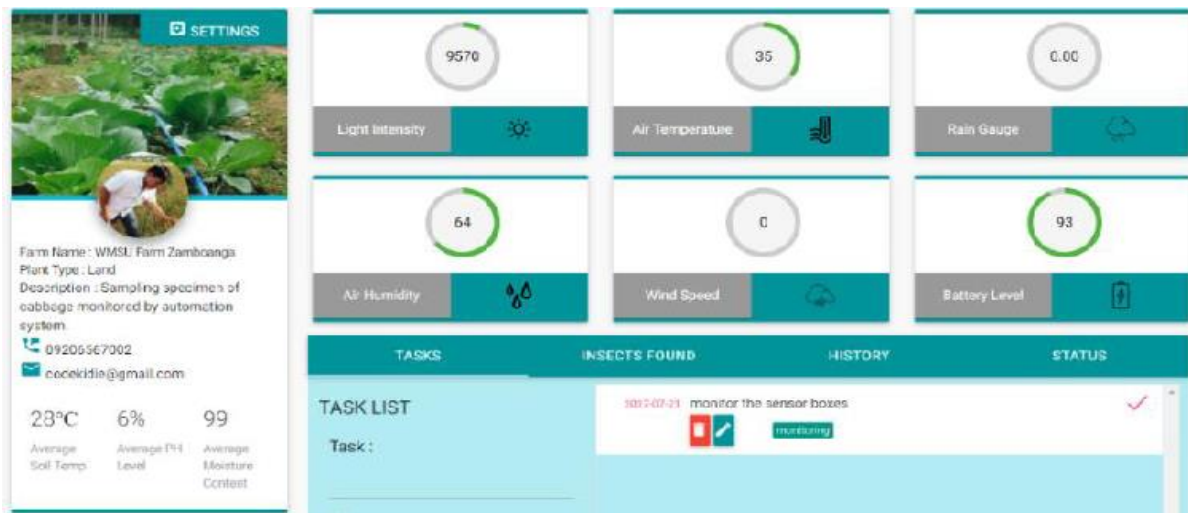


Figure 3.4 Web Platform for Monitoring conditions of the crops.

The web platform (Figure 3.4) enables monitoring of environmental and soil parameters. Within the experimental lot, 18 sensor boxes have been deployed in each row. These boxes, along with their respective sensor readings, are depicted in Figure 3.5. Additionally, 18 automation boxes are installed in every pipe across the 16 rows. Prior to activating these devices, they are registered using a straightforward barcode scanning process via a mobile phone.

The system performs a quadratic regression each time data is transmitted from a sensor box, thereby ensuring a single, unified reflection of the farm's soil condition. Figure 3.6 offers a graphical representation of the central device's battery health, providing farmers with crucial information about its power capabilities.

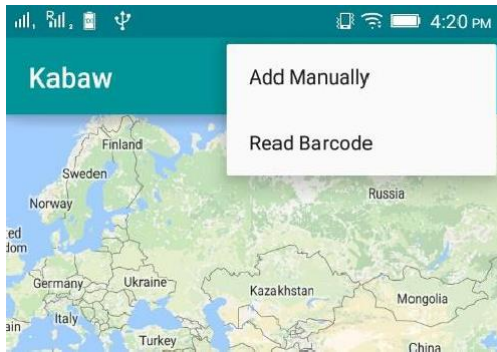


Figure 3.5 Barcode scanning for Sensor and Automation Box registration.



Figure 3.6 Active 18 sensor boxes deployed in the field.

The figure 3.7 also includes a history tab that provides a comprehensive overview of the crops' condition and allows for subscription to pertinent topics where changes can be observed. To represent the data in an understandable visual and is useful for engineers and scientists, the proponents used a free and open-source graph API from Plotly as shown in Figure 3.8. Users may also download their raw data in an excel file.

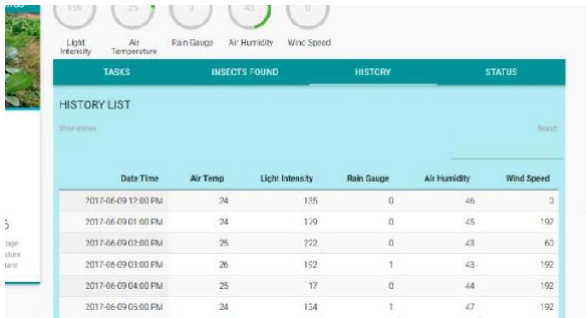


Figure 3.7 History of the gathered data from the environment and soil parameters.

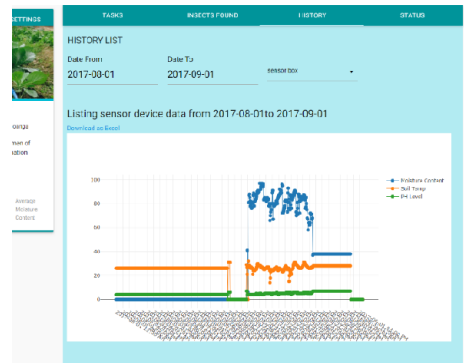


Figure 3.8 Graphical representation of the collected data.

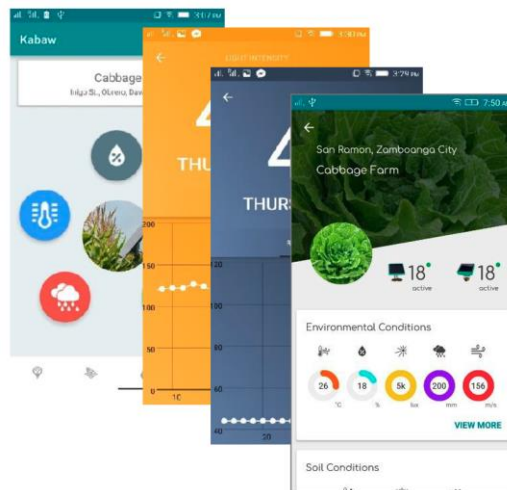


Figure 3.9 Android Mobile Application reading the sensed data.

Monitoring of environmental and soil parameters is accessible on mobile devices through a user-friendly interface (UI) (Figure 3.9). The UI, considering the age of the target users, features bright, enlarged fonts, buttons, and interface elements. Users can remotely view sensor data by initiating a connection to the MQTT broker. An HTTP server running on the same machine facilitates user login to their respective farms or gardens, enabling them to monitor ambient plant conditions, moisture levels, and irrigation status. Additionally, an automatic irrigation schedule is generated based on collected data and a one-time system setup, typically utilizing neural networks.

- 2.) *Fit the circuitry to its defined enclosures free from the effects of a harsh environment. Figure 3.10 presents the placement of the chip with the 2200 mAh Lithium-ion and testing the functionality of the sensors. The whole setup is then covered by the 5V, 1W, Monocrystalline solar panel. The photovoltaic solar panel is used as an energy harvesting component of both the sensor and the automation box. The enclosure of the boxes is 3D printed and take 6 to 7 hrs. to complete.*



Figure 3.10 Circuitry Placement

Along with the progress is the fabrication of the stainless-steel enclosure of the central device, as shown in Figure 3.11, with 610 cm x 377 cm in size. One careful consideration, aside from the ventilation and rigidity, is the addition of wire systems for path/route planning. Taking this into account during product design rather than adding them later accelerates the development process, saves time and rework costs, and helps to ensure efficient product assembly and serviceability.



Figure 3.11 Central device Stainless Steel Fabrication

After multiple designs and trials in 3D printing and steel fabrication, the final design is considered, especially it has to withstand harsh conditions and satisfy the beauty and strength.

- 3.) *Estimates the irrigation schedule for a complete season and automatically irrigated based on NN.* Though the soil water availability can be controlled using irrigation, the ambient conditions are still uncontrollable, thus creating a complicated relationship between them. This implies that the decision taken based on these values does not entirely reflect the needed one. To relate the required output with the sensor inputs, simple equations are not enough, and so here, NN is employed for getting the precisely accurate output. A crop IN requirement database is used to train the NN shown in figure 3.2. The Bayesian regularization algorithm is used in training done by the network. Weights and biases obtained post-training are used to compute the output and typical mode outcome on the selection of Adaptive mode.

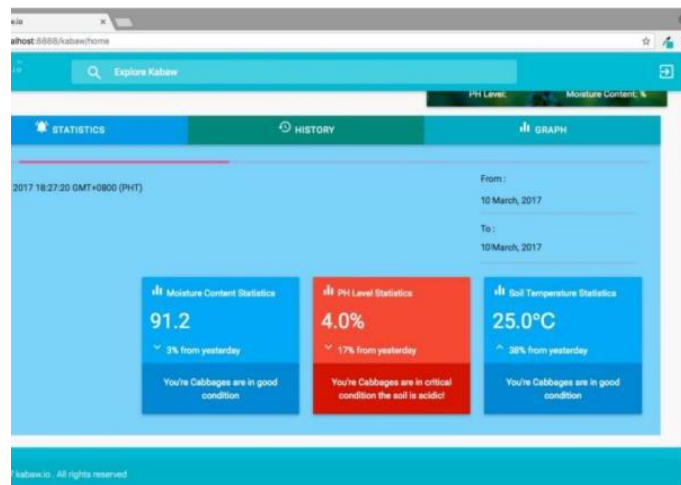


Figure 3.12 Results of crop condition and evaluation.

After setting the inclusive dates, the application will show the summary of the environmental and soil condition of the crops. Thus, giving the farmer a clearer picture of what's going on the farm, as shown in Figure 3.12. The said results of evaluation based on the algorithm will influence sending a request to the automation box to trigger the irrigation flow.

IV. CONCLUSION

In our research, we successfully developed a comprehensive farm monitoring system equipped with automated irrigation. Utilizing sensor boxes with advanced sensors and wireless connectivity, the system continuously gathers soil and environmental data, processed by a central device that uses initial farm information and current data trends to create an optimal, adjustable irrigation schedule. The data is relayed to a cloud platform via an MQTT broker, allowing for effective remote farm monitoring and smarter water management, especially beneficial for water-scarce regions and farmers who cannot be on-site regularly. Looking forward, potential enhancements could include deploying the system across multiple farms, extending the lifespan of the sensor and automation boxes through communication technology optimization and battery usage reduction, and incorporating a farm management feature for online consultations on various farming issues. This study represents a crucial advancement towards smart, sustainable farming, underscoring the potential of integrating technology into agriculture for improved resource management and productivity, and we hope it paves the way for future studies in agricultural technology.

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