

Soil Analysis and Crop Advisory System Using ESP32 and IoT

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Abstract— The aim of this study is to present an IoT system for soil analysis and crop advising by ESP32. It is a multi-parameter sensing system, automatic irrigation system, soil-health assessment system, local visualisation system and cloud monitoring system. The Soil moisture, pH, temperature, humidity, nitrogen, phosphorus and potassium sensor data are connected, which is followed by a rule based decision logic process. The pump operates when soil moisture is below 35% but not when it is above 70% and when the temperature is above 40 °C or the humidity is above 80%, environmental alerts are sent. Moisture, pH, NPK and temperature conditions are assigned a score of 100 to determine if they are Excellent, Good, Average or Poor. The advisory layer provides advice on irrigation, soil treatment, fertiliser and crop. A local info shown on 16×2 I2C LCD and remote visualisation of data, in 8 data fields, provided by ThingSpeak. The experimental results consist of the created hardware, the cloud dashboard, the sensor trend, the pump response, the LCD outputs, and functional validation of the program rules.

“Keywords—ESP32, IoT, smart agriculture, soil analysis, crop advisory, NPK, automatic irrigation, ThingSpeak.”

I. INTRODUCTION

Agricultural production is a function of soil water availability, acidity or alkalinity, nutrient status and environmental circumstances. Continuous information will not be available during growth if moisture, temperature, humidity, pH or nutrient levels change, and periodic hand checks will provide information about broad field conditions. This need is fulfilled by the system implemented, a platform based on the ESP32 that integrates sensing, processing, automatic control, advisory functions, local display and cloud connection.

There are 7 parameters being monitored: Soil moisture, pH, temperature, humidity, nitrogen, phosphorus and potassium. The values measured are directly taken from the embedded decision rules. Soil moisture determines irrigation, local warnings are temperature and humidity based, a soil-health score is generated from six criteria and the advisory logic transforms measured conditions into suggestions for irrigation, lime, gypsum, fertiliser and crop. This solution does not need trained predictive model or an external computing server for providing decision support.

Accessibility of agricultural information is also covered by the system. The 16×2 I2C LCD keeps rotating through the measurements, the condition of the pump, and the crop suggestion and soil-health rating. The fields sent will be stored and graphed remotely by ThingSpeak. These local and remote interfaces enable the same embedded decision process to be viewed from the field unit and the IoT dashboard.

The novelty/innovation of this study is the combination of multi-parameter soil analysis, hysteresis control of irrigation, environmental alarms, weighted Soil-Health scoring, rule based crop and Soil-management advice and LCD monitoring and ThingSpeak visualisation in a single process on the ESP32. This means that the assessment is limited to operational outputs such as trend of sensors, state of control and instructions for action, display behavior, communication with cloud, and test conditions for functions.

II. RELATED WORK

The combination of irrigation control with linked sensing, nutrient evaluation and crop-related decision support is an area where smart-agriculture research has started to integrate. For this study, the literature surveyed comprised IoT solutions for smart farming [1], agricultural monitoring and control [2], soil nutrient management [3], smart irrigation [4, 5], AIoT-based soil management [6] and also crop recommendation systems with the integration of IoT and machine learning [7-10]. In these research, the most frequently cited soil moisture, pH, NPK, temperature and humidity are referred to as important inputs in agricultural activities.

The approaches surveyed vary in terms of their integration and complexity. Some concentrate on crop irrigation, some on monitoring cloud, some on nutrient status, and some aim to introduce machine-learning models for crop prediction. The ongoing project is based on a simple rule based architecture and will strive for integrating sensing, irrigation, soil-health assessment, advising logic, local display and remote visualisation. Many other studies focusing on IoT sensing, WSN, smart irrigation and agricultural analytics also validate the need for continuous linked measurement in precision agriculture [11]–[30].

A) Literature Positioning and Research Gap

A review of the literature shows that many different agricultural systems have been implemented that address single or just a few functions in detail, such as irrigation, nutrient monitoring, cloud observation, or machine learning crop recommendation. This project is distinctive as it has seven measurable metrics, automatic pump control, environment alarms, soil-health scoring, crop/soil advisory, LCD visualisation and ThingSpeak monitoring all in one integrated application. The main difference is this combination, not the employment of a complicated prediction model, as described in the project concept.

The following table summarizes the areas of literature that were considered in this project.

Research gap identified is a realistic system in which soil moisture, pH, NPK, temperature and humidity are measured simultaneously and correlated with the control and advisory functions in a quick manner. The solution for implementing is then geared towards transparent rules which can be run directly on the ESP32. The architecture is built to be monitored and managed in a routine way without having to deploy a remote inference server.

B) Existing Approaches and Design Rationale

Soil assessments are typically conducted in the field with the aid of a physical inspection or laboratory testing at regular intervals. These methods can provide accurate measurement but they are not continuous measurements of moisture, temperature, humidity or nutritional condition and are not necessarily representative of short term changes. This is improved by automatic irrigation systems that incorporate soil-moisture sensors to control watering, however, a moisture system provides little information about the soil's pH, NPK availability, soil environment, or suitability for a range of management practices.

IoT based monitoring gives a better level of visibility in the field by transmitting measurements to cloud based platforms for remote monitoring. However, even monitoring will involve the user in understanding the significance of the sensor readings and what steps to take with regard to watering, soil treatment or fertiliser intervention. Smarter systems utilize machine learning to make the selection of crops, yields, disease analysis or management of fertilisers. These systems need representative datasets, trained models, additional software layers and computers, etc. The clever architecture is designed to use transparent embedded rules to allow the monitoring, irrigation, scoring and advisory tasks to be performed by the same ESP32 controller.

The design reason is hence functional integration instead of algorithmic complexity. Moisture, pH, NPK, temperature and humidity are complimentary information regarding the field conditions. These measurements can be combined in a single processing pathway and multiple outputs can be generated through a single acquisition cycle using the controller: irrigation state, environmental alert state, soil-health score, soil-treatment advice, crop recommendation, LCD information, Serial Monitor output, and cloud telemetry. Additionally, the unified method adds an additional advantage of easier traceability of the visible output to the sensor circumstance that created it.

C) Research Gap Addressed by the Implemented System

The literature review indicates the gap between simple monitoring systems and platform-driven agriculture systems, which are heavily dependent on data. Systems designed to just irrigate may not consider nutrients or pH, and systems that analyse nutrients may not have closed-loop water control. Cloud-only monitoring can be useful for improving data access, but does not automatically translate to having a local response when field conditions reach a critical threshold. Machine-

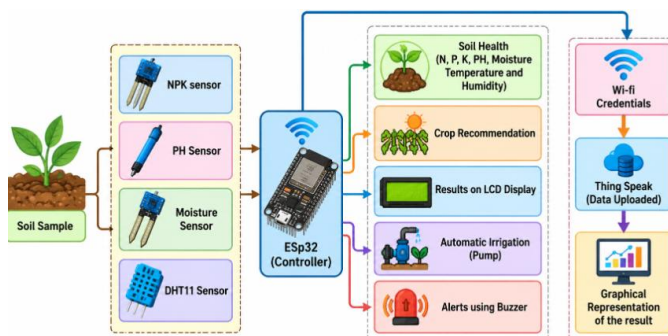
Learning crop prediction on the other hand can give complex crop recommendations, which might be too much when a simple connection between measured conditions and clear control and advising rules is required.

The developed system addresses this gap as it connects the sensing, decision, actuation, advising and communication by eliminating the need for separate computing platforms. Both the pump and buzzer controls, as well as the logic for the calculations, is accomplished by the same ESP32 that receives the measurements from the field. The same ESP32 that receives the field measurements also handles the logic for the pump and buzzer, the soil-health score calculation, the LCD refresh cycle, and the packing of the results for ThingSpeak. Information flows directly from soil state to a user visible response, and is inspectable.

III. MATERIALS AND METHODS

A) System Architecture and Sensing Layer

The primary control and processing unit is the ESP32. The pin connections for soil moisture sensor is GPIO 34, pH sensor is GPIO 35 and DHT11 is GPIO 4. Collect nitrogen, phosphorus and potassium from NPK sensor with Modbus RTU on UART2, interface with MAX485. The relay and the water pump are controlled by GPIO 26. This buzzer is controlled by GPIO 27. This LCD is programmed to communicate with I2C. The overall signal and decision flow is shown in figure 1.



“Fig. 1. Functional block diagram of the soil analysis and crop advisory system.”

“TABLE I. IMPLEMENTED SENSOR, CONTROL, AND CLOUD CONFIGURATION”

Component	Interface	Implemented role
Soil moisture	GPIO 34	Moisture monitoring and irrigation control
pH sensor	GPIO 35	Acidity/alkalinity monitoring and advisory
DHT11	GPIO 4	Temperature and humidity monitoring
NPK sensor	GPIO 16/17 + RS485	N, P, K acquisition through Modbus RTU
Relay / pump	GPIO 26	Automatic irrigation actuation
Buzzer	GPIO 27	Temperature/humidity alert indication
16×2 LCD	I2C	Local values, advisory, pump and health display
ThingSpeak	Wi-Fi/HTTP	8-field remote monitoring including pump state

B) Signal Processing, Irrigation, and Alerts

The raw output of the soil moisture ADC is then mapped to a percentage with the raw limits programmed in the firmware and limited to 0–100%. The average of 10 ADC values is used for pH, voltage is obtained by $V = \text{ADC} \times 3.3/4095$ and the relation programd is applied, $\text{pH} = 2.0V$. Data from the DHT11 is first checked and then the temperature and humidity are stored. The NPK values are transmitted digitally at 9600 baud, 8 bits, no parity and 1 stop bit.

There are two thresholds for automatic irrigation which provide a hysteresis. When moisture level is below 35% the relay is energised and the pump is turned ON. When the moisture goes above 70% the pump goes OFF, the prior state is kept between these limits. Buzzer for environmental alert: temp $\geq 40^\circ\text{C}$ or humidity $\geq 80\%$. The same sensor data is used for observation and for instant actuation, due to these criteria.

C) Soil-Health Assessment and Crop Advisory

The soil-health score has six predetermined conditions, a maximum score of 100. Moisture, pH and nitrogen are worth 20 points apiece, phosphorus and potassium are worth 15 points each and temperature is worth 10 points. The scoring rule used is using indicator function $I(\cdot)$:

$$SHS = 20I(40 \leq M \leq 70) + 20I(6 \leq pH \leq 7.5) + 20I(N \geq 150) + 15I(P \geq 70) + 15I(K \geq 120) + 10I(20 \leq T \leq 35).$$

“TABLE II. SOIL-HEALTH SCORING AND CLASSIFICATION”

Parameter	Condition	Points
Soil moisture	40–70%	20
pH	6.0–7.5	20
Nitrogen	≥ 150	20
Phosphorus	≥ 70	15
Potassium	≥ 120	15
Temperature	20–35°C	10
Health class	≥ 80 Excellent; ≥ 60 Good; ≥ 40 Average; < 40 Poor	Max 100

The score interpretation is: Excellent (≥ 80); Good (≥ 60); Average (≥ 40); Poor (< 40). The advising function is deterministic based on a sequence of conditions, each of which is tested with the same sensor information. Low moisture = Irrigate. If the pH is acidic = Add Lime or Gypsum. Insufficient N/P/K = Fertiliser. Moisture/temperature ranges = Rice, Cotton, Tomato, Groundnut or Vegetables.

“TABLE III. CROP AND SOIL-MANAGEMENT RECOMMENDATION RULES”

Condition	Advisory output
Moisture $< 35\%$	Irrigate
pH < 5.5	Add Lime
pH > 7.5	Gypsum
N < 100 or P < 50 or K < 100	Fertilizer
Moisture $\geq 70\%$ and T $\geq 25^\circ\text{C}$	Rice
Moisture 40–60% and T 25–35°C	Cotton
Moisture 50–70% and T 20–30°C	Tomato
Moisture 35–55%	Groundnut
Other conditions	Vegetables

D) Local Display and IoT Communication

There are six rotating pages on the LCD: Moisture (pump status), temperature (humidity), pH (nitrogen), phosphorus

(potassium), crop suggestion, and soil-health score/class. Wi-Fi and HTTP are used to send data from the sensors to ThingSpeak, where the data is stored every 2 seconds, roughly, and displayed every 3 seconds, on the LCD pages. Data is sent from the sensors to ThingSpeak via Wi-Fi and HTTP and stored approximately every 2 seconds, and displayed roughly once every 3 seconds, on the LCD pages. The data is sent about every twenty seconds.

E) Continuous System Operation Cycle

The ESP32 initialises sensor interfaces, LCD, relay, buzzer, RS485/Modbus communication and creates a Wi-Fi connection on start-up. Normal functioning reads the soil moisture, pH, DHT11 temperature/humidity and NPK readings. Raw values are converted into representation that can be used by the decision logic. If the DHT11 is not working properly, the previous value obtained from the environment is not lost.

The next stage is to check the moisture for irrigation and temperature/humidity for alarms. There are then 6 scoring conditions and soil-health scores are given based on these conditions. The points then are translated to Excellent, Good, Average or Poor. The advice sequence evaluates the low moisture, acidic/alkaline pH, low nutrient levels and programd moisture/temperature combinations for crop recommendations. The results are then sent to LCD, pump state and (as applicable) advisory and soil health data are sent to the LCD, Serial Monitor and ThingSpeak.

The operation is not event-limited and is cyclic. Every 2 seconds (approx.) the sensors are acquired, every 3 seconds (approx.) the LCD pages rotate and finally every 20 seconds (approx.) the ThingSpeak refreshes. This allows fast local sensing and control decisions to be made while the cloud upload cycle is still going, so the embedded system can still make irrigation and alert decisions while the user isn't actively monitoring the cloud dashboard.

F) Layered IoT Architecture and Enabling Technologies

The system can be broken down into five layers of functions. Sensor: Soil moisture, pH, DHT11 and NPK sensors are used. The processing/control layer is created with the ESP32 in mind and processes, thresholds, scores soil health, provides suggestions, controls the pumps and controls the buzzer. Cloud access is via Wi-Fi, the NPK sensor is via Modbus RTU over RS485 and the LCD is via I2C. Application/monitoring layer: LCD and the ThingSpeak dashboard, Cloud layer: ThingSpeak.

The implementation is based on Arduino programming environment and libraries WiFi.h, HTTPClient.h, Wire.h, LiquidCrystal_I2C.h, ModbusMaster.h and DHT.h. The software interfaces to the communication and peripheral functions needed by the design are provided by the libraries. The irrigation or advice decision logic is not stored where the irrigation or advice is given, but instead is stored on the ESP32 and ThingSpeak is used to represent the data.

G) Design Characteristics

The following six aspects are emphasized in the design of the project: real-time monitoring, automatic control, local monitoring, remote monitoring, multi-parameter analysis and rule based decision assistance. Additional local alert system for

immediate warning when temperature or humidity is surpassed program limits. The sensor acquisition, decision logic, actuation, display and communication are synchronized while the sensor is functioning, and the whole cycle is repeated continuously.

H) Data Path, Timing, and Interface Coordination

The controller is responsible for getting the updated measurements at the beginning of each cycle and for updating the variables in the decision logic. The moisture and pH channels are taken from Analogue ADC measurements, DHT11 provide digital environmental data and the NPK values are passed through the RS485/Modbus route. The control decisions are then uploaded to the cloud, and executed locally until the cloud upload time. The pump or buzzer response is not delayed by the somewhat slow ThingSpeak transmission interval.

The interfaces have different update frequency as they are used for different purposes. The sensor acquisition is about two seconds, providing responsive local monitoring and control. A user can see the six information pages without having to rotate the display too much, the LCD rotation is about three seconds. Uploads to ThingSpeak at approximately 20 seconds utilize unnecessary network bandwidth, yet still enable a time-series representation of the primary metrics, and the pump condition. While testing, it is possible to still use the Serial Monitor to view values and warnings inside the device in greater detail.

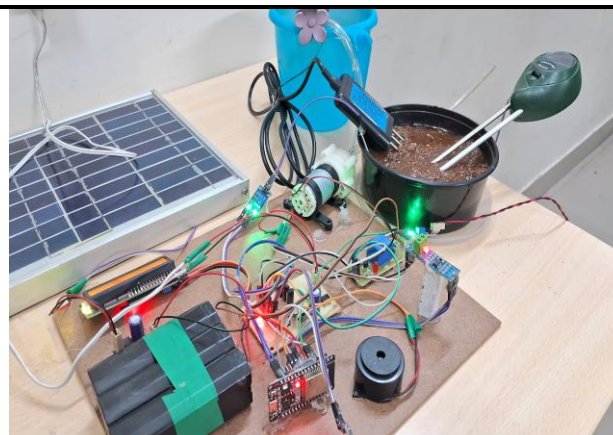
I) Decision Transparency and Traceability

Each advisory conclusion may be associated with a certain regulation. Moisture thresholds are directly related to irrigation; acidic or alkaline limits to pH treatment advice; program N/P/K limits to fertiliser advice; and precise moisture and temperature ranges to crop recommendations. This is the same for the soil-health score as each point contribution comes with a condition and a weight. In an embedded agricultural application, this transparency is beneficial because a user can compare before and after actions as well as a condition that has been programmed in the program without having to interpret an opaque model output.

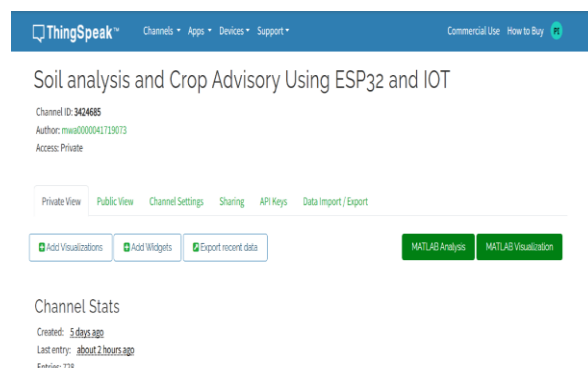
IV. EXPERIMENTAL RESULTS

A) Integrated Hardware and Cloud Dashboard

The hardware implemented is a single working set up that includes ESP32, soil moisture and pH sensors, DHT11, NPK sensor, MAX485 interface, relay, pump, buzzer and LCD. Figure 2 shows the fully constructed system. The selected sensor fields and pump condition were sent to the ThingSpeak channel as illustrated in Figure 3. All of these outputs are used to validate the embedded acquisition/control and distant IoT observation correlation.



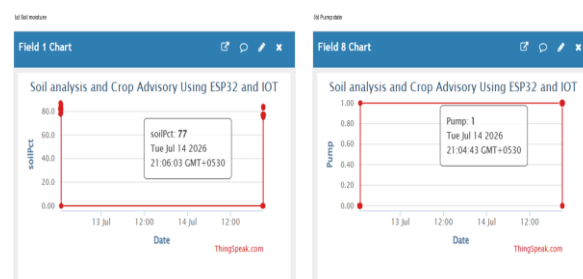
“Fig. 2. Implemented real-time soil analysis and crop advisory hardware.”



“Fig. 3. ThingSpeak dashboard for remote monitoring of the implemented system.”

B) Soil-Moisture Monitoring and Pump Control

The controlling input for irrigation is the soil-moisture graph. In the example of the ThingSpeak sensor, the status of the moisture sensor is set to 77% and the status for the independent pump sensor is set to binary. For program irrigation values greater than 70% are pump-OFF; values less than 35% are pump-ON. This sensing and acting interaction is illustrated with two outputs from the clouds in Figure 4.

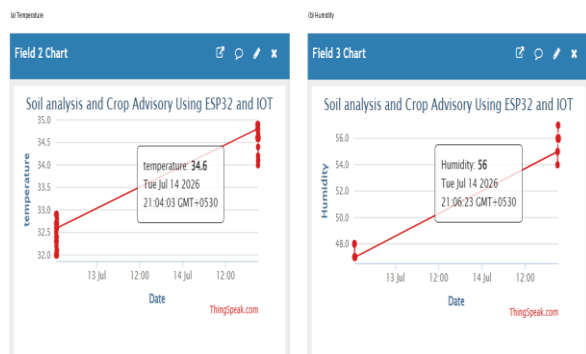


“Fig. 4. Soil-moisture and pump-state outputs used for automatic irrigation monitoring.”

The two-threshold technique is important because if there was only one switching threshold, the relay could switch many times if the moisture content fluctuates around the threshold. The hysteresis in the applied voltage maintains the previous pump state in the range of 35-70% and changes the state when the voltage crosses one of the two thresholds.

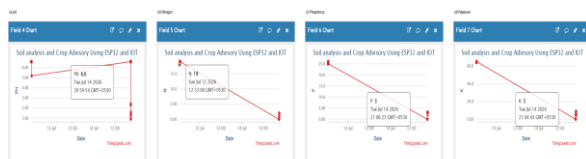
C) Temperature, Humidity, pH, and NPK Results

Environmental charts show the temperature to be 34.6 °C and the relative humidity 56%. Values are below the program limits of buzzer: 40 °C and 80% respectively. The temperature value is also in the range of 20-35 °C contributing 10 points to the soil health score. The paired DHT11 results are sent to ThingSpeak as illustrated in figure 5.



“Fig. 5. Temperature and humidity outputs transmitted through the IoT channel.”

The pH chart uses a value of 6.6 to represent a range of values from 6.0 – 7.5 that do not trigger the Add Lime (<5.5) or Gypsum (>7.5) rule. The nutrient levels on the NPK charts are for soil-health and fertilizer-advisory purposes. Shown are representative points: N=19, P=3, K=5. These nutrient readings illustrate the type of level of nutrient condition the fertiliser advice rule is designed to detect.



“Fig. 6. pH and NPK monitoring outputs from the ThingSpeak monitoring results.”

“TABLE IV. REPRESENTATIVE VALUES VISIBLE IN THE THINGSPEAK RESULT PLOTS”

Parameter	Representative value
Soil moisture	77%
Temperature	34.6°C
Humidity	56%
pH	6.6
Nitrogen	19
Phosphorus	3
Potassium	5
Pump state	1 (ON)

D) LCD Output, Advisory Presentation, and Functional Tests

The LCD provides instant local input when not connected to cloud access. It has pages that display sensor readings, the pump status, a crop recommendation and a soil-health class. The processed decisions are made visible – examples of LCD output include pump states and advisory/health messages.



Fig. 7. LCD outputs for measured conditions, pump state, crop advisory, and soil-health information.

The functional validation was carried out with pre-defined situations that represent the rules applied. Test set contains pump on/off, buzzer conditions, pH based treatment of soil, nutrient based fertiliser advise, LCD display, transmission to ThingSpeak and reconnection to Wi-Fi. Some of the answers predicted are summarised in Table V.

“TABLE V. FUNCTIONAL VALIDATION OF THE IMPLEMENTED RULES”

Test	Input / condition	Expected response
TC01	Moisture <35%	Pump ON
TC02	Moisture >70%	Pump OFF
TC03	Temperature ≥40°C	Buzzer ON
TC04	Humidity ≥80%	Buzzer ON
TC05	pH <5.5	Add Lime
TC06	pH >7.5	Gypsum
TC07	Low N/P/K	Fertilizer
TC08	Valid sensor values	LCD displays readings
TC09	Wi-Fi available	Upload to ThingSpeak
TC10	Wi-Fi disconnected	ESP32 reconnects

Experimental results indicate that all of the main functions complement each other: sensors measure soil and environmental data; the ESP32 runs the program rules; the relay, pump and buzzer give physical responses; the advisory logic gives understandable actions; the LCD is a local information provider and ThingSpeak is a distant visualisation provider. The study therefore takes a different approach to using a functional embedded control-and-advisory system, instead of a statistical classifier and thus does not use accuracy, precision, recall, F1-score, MAE, RMSE or R² as model-performance measures.

E) Integrated Result Discussion

The experimental results reveal the whole sensing-to-action chain realised on the ESP32 platform. Soil moisture is used for irrigation status based on 35% ON and 70% OFF threshold and comparison of temperature and humidity is done with the program buzzer limitations. The pH and NPK channels give soil-health scores and soil-management tips. The LCD provides the processed readings, pump state, advisory output and health classification locally. The eight fields observed are stored in ThingSpeak for remote viewing.

The research focuses on a rule-based embedded monitoring and control system instead of trained classification or regression model. The key indicators of relevance are the observed sensor output, the threshold response, the soil health classification, the creation of the soil health advisory, the behaviour of the actuators, and the effective communication with the cloud. The major constraints on implementation are sensor calibration and a fixed DT and network availability to visualise the sensor data in the cloud. The ESP32 still powers the local watering, as well as the alarms, scoring and LCD operations.

V. CONCLUSION AND FUTURE SCOPE

Created system is an integrated ESP32 based system for smart agriculture using soil moisture, PH, temperature, humidity and NPK values. These inputs are used for automatic irrigation, environmental alarms, weighted soil health assessment and rule-based crop and soil management recommendations. There are complementary views of the same operating state given by local LCD pages and cloud-based ThingSpeak plots, and functional testing validate the expected responses in key sensor, control, advisory, display and communication states.

Further considerations for future work are a special mobile interface, history dashboards, meteorological and rainfall data, different irrigation zones, solar energy, distributed ESP32 sensing nodes, automated fertiliser dispensing, and crop disease identification via image processing. With sufficient historical data regarding soil, the weather, the crops and the yields, data-driven recommendation models can be added as an additional layer of recommendations to the existing sensor, actuation and IoT infrastructure.

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