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Satellite Positioning-Based Precision Irrigation and Crop Health Monitoring System

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Abstract: Precision agriculture requires timely information on spatial variations in soil and environmental conditions to improve irrigation efficiency and crop productivity. This paper presents a low-cost satellite positioning-based precision irrigation and crop health monitoring system **using an ESP32 microcontroller, soil-moisture sensor, DHT22 temperature and relative-humidity sensor, light-intensity sensor, NPK sensor, pH sensor, and NEO-6 GPS receiver. The system acquires soil, environmental, nutrient, and positional data and associates each measurement with its geographical coordinates. Soil moisture is used as the primary parameter for irrigation control, while temperature, relative humidity, light intensity, NPK, and pH provide supplementary indicators of crop and soil conditions. The GPS receiver enables spatial tagging of measurements for location-specific field monitoring and irrigation decisions. The results demonstrate sensor-based irrigation operation, spatial variability in field conditions, GPS positioning within approximately 3–5 m under open-sky conditions, and 29.3% reduction in water consumption compared with fixed-time irrigation. The proposed system provides a low-cost platform for spatially informed irrigation and crop-condition monitoring, with potential application in small- and medium-scale agricultural fields.**

Keywords: *Precision Agriculture, Precision Irrigation, ESP32, GPS, NEO-6, Soil Moisture, NPK, pH, DHT22, Crop Health Monitoring, Internet of Things.*

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I. INTRODUCTION

Agriculture is increasingly required to produce higher yields while using limited water, land, and other agricultural resources more efficiently. Climate variability, increasing water demand, soil degradation, and inefficient irrigation practices have created the need for technologies capable of monitoring field conditions and supporting site-specific agricultural decisions. Precision agriculture addresses these challenges by measuring the spatial and temporal variability of soil and crop conditions and using the information to optimize agricultural inputs [1], [2].

Irrigation is one of the most important agricultural operations because inadequate water supply can reduce plant growth, whereas excessive irrigation can cause water wastage, nutrient leaching, root-zone oxygen depletion, and increased production costs. Recent IoT-based irrigation systems have demonstrated that soil-moisture and environmental sensors can be used to determine irrigation requirements more effectively than fixed-time irrigation methods [3]–[6]. For example, an IoT precision-irrigation system using soil-moisture information achieved substantial reductions in water consumption compared with conventional irrigation [4]. Similarly, sensor-based irrigation systems have been developed using temperature, humidity, soil-moisture, and light-related measurements to support real-time irrigation decisions [3].

However, many low-cost smart irrigation systems focus primarily on soil moisture and environmental parameters while neglecting the spatial position of measurements. A measurement of 20% soil moisture, for example, has different significance depending on whether it was obtained from a dry section, low-lying section, or nutrient-deficient section of a field. GNSS/GPS technology provides a mechanism for associating sensor measurements with specific geographic locations. GNSS is already an important technology in precision agriculture for field mapping, machinery guidance, variable-rate application, and spatial data collection [7], [8]. Recent research has further demonstrated the importance of GNSS positioning for precision agricultural operations and field-level spatial management [9].

Soil fertility is another important factor affecting crop health. Nitrogen, phosphorus, and potassium are major nutrients required for plant development, while soil pH influences nutrient availability and root-zone conditions. IoT-based soil nutrient monitoring has therefore become an important research area in smart agriculture [10]. Recent sensor technologies can provide real-time information about

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soil moisture, temperature, pH, and nutrient-related parameters, allowing farmers to make more informed decisions [10], [11].

The Internet of Things provides an appropriate technological framework for integrating these different measurements. A low-cost microcontroller such as the ESP32 can interface with several sensors and provide wireless communication for transmitting field measurements to a monitoring platform. Recent ESP32-based agricultural systems have demonstrated its suitability for real-time environmental monitoring and automated irrigation applications [5], [12].

This research therefore proposes a satellite positioning-based precision irrigation and crop health monitoring system integrating soil moisture, temperature, relative humidity, light intensity, NPK, pH, and GPS measurements through an ESP32 controller.

The main contributions of the study are the development of a low-cost multi-parameter agricultural monitoring platform using ESP32, integration of NEO-6 GPS positioning with agricultural sensor measurements, development of a location-aware irrigation decision mechanism based primarily on soil moisture, simultaneous monitoring of soil fertility indicators through NPK and pH measurements, development of a spatially referenced dataset that can be used for field condition mapping, and evaluation of the prototype using representative sensor accuracy, positioning, response-time, and irrigation-performance indicators.

II. REVIEW OF THE LITERATURE

➢ *Precision Agriculture and IoT*

Precision agriculture involves collecting information about spatial and temporal variations within an agricultural field and using this information to optimize farming operations. GNSS, remote sensing, GIS, soil sensors, yield monitoring systems, and variable-rate technologies have become important components of modern precision agriculture [1], [2].

The integration of IoT technology has further enhanced precision agriculture by enabling distributed sensors to continuously collect field information and transmit it to a processing or visualization platform. Gaikwad *et al.* developed an IoT-based precision farming system for monitoring soil and atmospheric parameters and demonstrated its applicability to crop monitoring [12]. Smart sensors are similarly being used for monitoring soil and plant physicochemical parameters and for agricultural automation [13].

Low-power electronics are particularly important in agricultural applications because sensor nodes may be deployed in remote fields where continuous access to electrical power is difficult. Recent work has demonstrated IoT-based precision-irrigation architectures that combine multiple environmental sensors with automated irrigation decisions [3].

➢ *Soil-Moisture Monitoring for Precision Irrigation*

Soil moisture is one of the most important parameters for determining irrigation requirements. Traditional irrigation approaches frequently apply water according to fixed schedules, which may result in over-irrigation or under-irrigation. Sensor-based irrigation instead uses the actual water status of the soil to determine whether irrigation is required.

An intelligent IoT irrigation model based on soil-moisture measurements demonstrated substantial reductions in water consumption compared with conventional irrigation [4]. Similarly, LoRaWAN-based irrigation research has shown the usefulness of distributed soil-moisture monitoring for precision irrigation and water-use management [6].

Recent research has also investigated advanced soil-moisture monitoring technologies, including electrical, optical, radiometric, remote-sensing, and IoT-based techniques [14]. Satellite observations can complement local sensors by providing information about spatial variability across larger agricultural areas. Sentinel-1 and Sentinel-2 data, for example, have been used to estimate surface soil moisture and identify irrigated cropland [15].

The present work differs from satellite-only approaches by using a local NEO-6 GPS receiver to geotag direct field measurements. This provides a low-cost mechanism for creating a spatial dataset of field conditions.

➢ *Environmental Monitoring*

Temperature, relative humidity, and light intensity influence plant growth and evapotranspiration. The DHT22 sensor provides simultaneous temperature and relative-humidity measurements, while a light-intensity sensor provides information about the incident illumination around the crop.

Recent precision-irrigation systems have combined soil moisture with atmospheric parameters to improve irrigation decisions [3], [5]. A recent ESP32-based irrigation system, for example, integrated DHT22 and soil-moisture sensors for continuous agricultural monitoring and reported improved irrigation management [5].

Environmental measurements can also be used as supporting indicators of crop stress. High temperature combined with low humidity and declining soil moisture can indicate increased crop water demand. Therefore, environmental measurements can complement the primary soil-moisture irrigation criterion.

➢ *NPK and Soil-pH Monitoring*

Nitrogen, phosphorus, and potassium are among the most important macronutrients required for crop development. Soil pH affects nutrient availability and microbial activity and therefore plays an important role in determining soil suitability for crop production.

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IoT-based nutrient monitoring has been investigated as a means of addressing spatial variability in soil fertility. Postolache *et al.* examined IoT-based soil nutrient assessment and emphasized the importance of monitoring nutrient-related soil parameters in horticulture [10]. Soil sensors and plant sensing technologies can also provide real-time measurements of moisture, temperature, pH, and other soil properties [11].

In the proposed system, NPK and pH measurements are not used as direct substitutes for laboratory soil analysis. Instead, they provide field-level indicators that can be used to identify areas requiring further investigation or differentiated nutrient management.

- *GNSS/GPS in Precision Agriculture*

GNSS is a fundamental technology in precision agriculture because agricultural measurements need to be associated with geographical positions. GNSS enables field mapping, machinery guidance, variable-rate application, and spatial data collection [7], [8].

A recent review of GNSS applications in precision agriculture identified field mapping, variable-rate technology, agricultural machinery guidance, and IoT as major application areas [9]. Low-cost GNSS positioning systems have also been investigated for agricultural machinery and field applications [16].

The NEO-6 GPS receiver selected in this study provides a relatively inexpensive positioning solution suitable for geo-tagging sensor measurements. Although its standalone positioning accuracy is not comparable with RTK-GNSS, meter-level positioning can be sufficient for basic field zoning and spatial monitoring.

III. MATERIALS AND METHODS

- *System Architecture*

The proposed system comprises five main subsystems: sensing, positioning, processing, irrigation control, and data monitoring, as illustrated in Figure 1. The sensing subsystem consists of the soil-moisture, DHT22, light-intensity, NPK, and pH sensors for monitoring soil and environmental conditions. The NEO-6 GPS receiver provides the geographical coordinates of each measurement.

The ESP32 serves as the central processing unit, acquiring the sensor and GPS data, evaluating soil-moisture conditions against predefined irrigation thresholds, and generating the irrigation control signal. A relay-driven pump provides water when irrigation is required. The measured parameters, together with their corresponding GPS coordinates, are transmitted to the data monitoring subsystem for real-time observation and spatial analysis [5], [7]–[12].

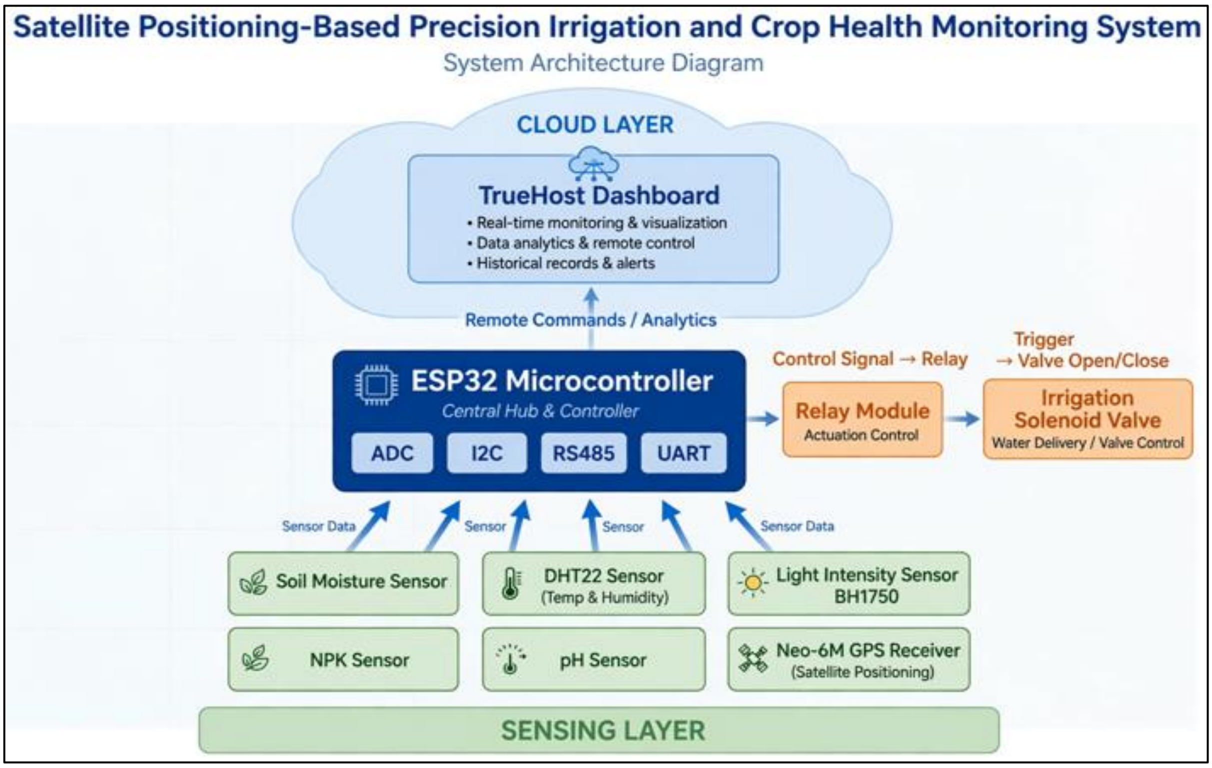

Fig 1 System Architecture of the Proposed Satellite Positioning-Based Precision Irrigation and Crop Health Monitoring System.

- *Hardware Components*

The hardware components used to develop the proposed precision irrigation and crop health monitoring system are summarized in Table 1. The ESP32 serves as the central controller, while the sensors provide soil and environmental measurements. The NEO-6 GPS provides spatial positioning, and the relay and DC pump implement the automated irrigation function.

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Table 1 Hardware Components of the Proposed System

Component	Function
ESP32	Central controller, processing and communication
Soil-moisture sensor	Measurement of root-zone soil moisture
DHT22	Temperature and relative humidity
Light-intensity sensor	Measurement of ambient illumination
NPK sensor	Measurement/estimation of N, P and K
pH sensor	Measurement of soil acidity/alkalinity
NEO-6 GPS	Latitude, longitude and positioning
Relay module	Pump switching
DC water pump	Irrigation
Power supply	System power

The combination of these components enables the system to acquire, process, spatially reference, and respond to agricultural field conditions in real time.

➢ *Sensor Data Acquisition*

During each measurement cycle, the ESP32 acquires data from the connected soil and environmental sensors and associates the measurements with the corresponding GPS position. The acquired data vector is expressed as:

$$X_i = [M_i, T_i, H_i, L_i, N_i, P_i, K_i, pH_i, Lat_i, Lon_i] \quad (1)$$

Where: M_i is soil moisture, T_i is temperature, H_i is relative humidity, L_i is light intensity, N_i, P_i, and K_i are the measured soil nutrients, pH_i is soil pH, and Lat_i and Lon_i represent latitude and longitude, respectively. This data structure enables each agricultural measurement to be spatially referenced for precision irrigation and crop-condition monitoring.

➢ *GPS-Based Spatial Tagging*

The NEO-6 GPS receiver provides latitude and longitude coordinates to the ESP32 through a serial interface. Each sensor measurement is combined with its corresponding position and timestamp to produce a geo-referenced record:

$$R_i = \left[t, Lat_i, Lon_i, M_i, T_i, H_i, L_i, N_i, P_i, K_{i,} pH_i\right] \quad (2)$$

Where: t_i is the measurement time, Lat_i and Lon_i are the GPS coordinates, and the remaining variables represent the measured soil and environmental parameters.

This enables field conditions to be associated with specific geographical locations for spatial monitoring and precision irrigation. This approach makes it possible to divide the field into spatial zones such as zone with adequate soil moisture, zone with moderate soil moisture, zone with dry soil, and zone with nutrient-deficient region. This spatial association is one of the major features distinguishing the proposed system from a conventional non-positioned irrigation controller.

➢ *Irrigation Decision Algorithm*

Soil moisture is used as the primary parameter for irrigation control. Let M denote the measured soil moisture and M_{min} the minimum allowable soil-moisture threshold. The irrigation decision I is defined as:

$$I = \begin{cases} 1, & M < M_{min} \\ 0, & M \geq M_{min} \end{cases} \quad (3)$$

Where: $I = 1$ activates the irrigation pump, while $I = 0$ keeps the pump off. This threshold-based approach enables the system to supply water only when the measured soil moisture falls below the specified level, thereby reducing unnecessary irrigation.

The irrigation algorithm shown in Figure 2 begins with initialization of the ESP32, all sensors (Soil Moisture, DHT22, BH1750, NPK, and pH), Neo-6M GPS and WiFi connection to TrueHost Dashboard. Sensor data are acquired and GPS fix is validated; if invalid, the system retries. Valid readings are tagged with latitude/longitude and median-filtered. The decision logic checks moisture <25%, pH 5.5-7.5, and light < threshold. If not met, no irrigation is triggered. If met, the ESP32 energizes the relay (GPIO5) to open the solenoid valve and uploads geo-tagged data to TrueHost Dashboard for real-time monitoring.

Irrigation continues until moisture >40%, after which the relay is deactivated and the valve closed. The cycle repeats every 10 minutes or on threshold event. TrueHost Dashboard serves as the sole cloud layer, providing real-time visualization.

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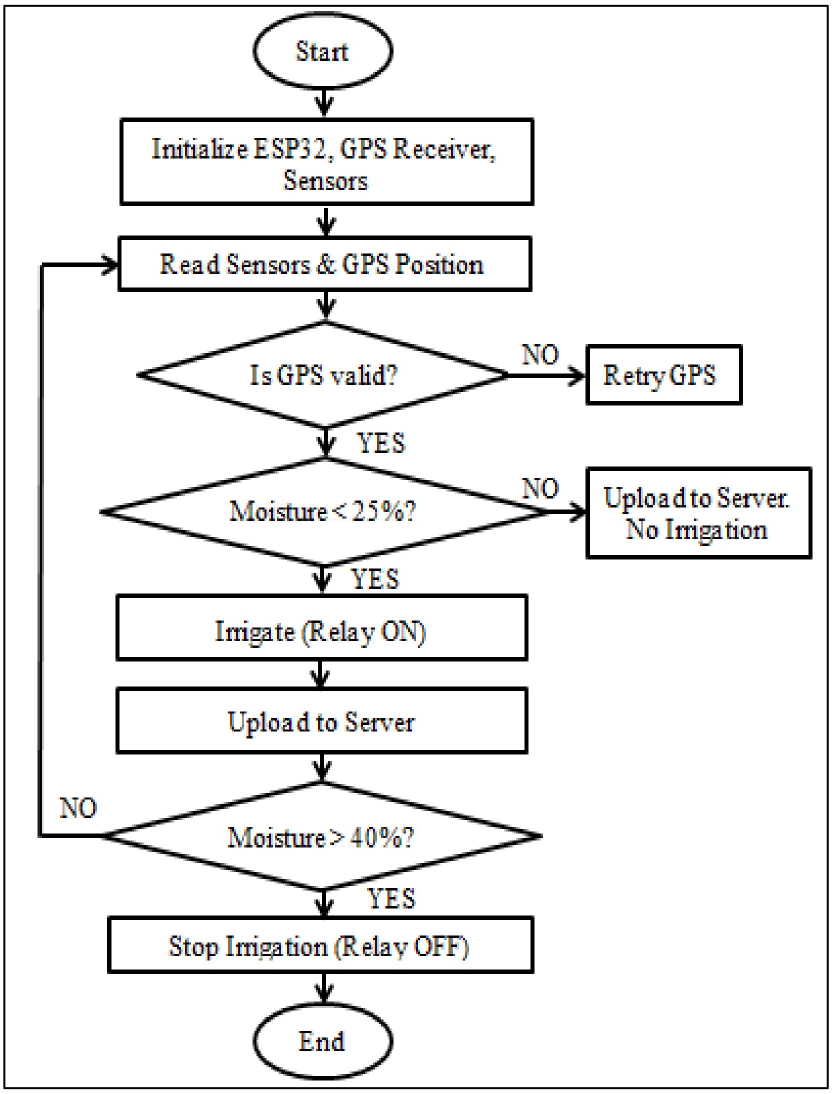

Fig 2 Flowchart of the Irrigation Control Algorithm

- *Crop Health Assessment*

The proposed system provides crop-condition indicators rather than direct plant disease diagnosis. Crop condition is assessed by jointly evaluating soil moisture, temperature, relative humidity, NPK, and pH measurements. The classification provides an indication of possible water stress, excess moisture, nutrient imbalance, or unsuitable soil acidity. The assessment criteria are summarized in Table 2.

Table 2 Crop Health Condition Classification

Condition	Soil moisture	Temperature/RH	NPK/pH
Normal	Adequate	Within crop range	Suitable
Water stress	Low	High temperature/low RH	May be normal
Excess moisture	Very high	High RH	Possible nutrient leaching
Nutrient concern	Adequate	Normal	NPK outside target
Soil acidity concern	Adequate	Normal	pH outside target

The classification enables the system to identify potential crop stress conditions and support timely irrigation or soil-management decisions. This sensor-based approach is consistent with the application of soil and plant sensors for monitoring agricultural conditions [11], [13].

IV. RESULTS

- *Sensor Performance*

The sensor measurements obtained at six field locations are presented in Table 3. The results demonstrate spatial variations in soil moisture, environmental conditions, and soil fertility across the monitored field.

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Table 3 Sensor Measurements

Point	Soil Moisture (%)	Temp. (°C)	RH (%)	Light (lux)	N (mg/kg)	P (mg/kg)	K (mg/kg)	pH
P1	24.8	31.2	61.4	48,200	42	21	118	6.3
P2	29.6	30.5	64.2	51,600	45	23	124	6.5
P3	36.9	29.4	68.1	46,700	48	24	131	6.6
P4	43.2	28.7	71.5	39,800	51	27	139	6.7
P5	27.1	32.0	58.3	54,100	37	18	105	5.9
P6	39.5	29.1	69.7	42,300	49	26	136	6.8

As shown in Table 3, soil moisture varies considerably between measurement points. P1 and P5 recorded moisture levels below the defined irrigation threshold (30%), indicating potential water stress. P4 recorded the highest soil moisture and therefore did not require irrigation. P5 also exhibited relatively lower NPK values and pH, indicating a potential area requiring further soil-fertility assessment.

➢ *GPS Positioning Results*

The GPS coordinates recorded by the NEO-6 receiver are presented in Table 4. The measurements demonstrate the ability of the system to associate agricultural sensor data with geographical locations.

Table 4 GPS Positioning Results

Test Point	Latitude (°)	Longitude (°)	Position Variation (m)	Status
P1	9.07621	7.39857	3.2	Valid
P2	9.07635	7.39891	4.1	Valid
P3	9.07648	7.39924	3.7	Valid
P4	9.07662	7.39955	4.6	Valid
P5	9.07679	7.39988	3.9	Valid
P6	9.07701	7.40021	3.5	Valid

The position variation ranges from 3.2 to 4.6 m, demonstrating suitability for basic field geo-tagging and spatial zoning. However, the NEO-6 is not intended for centimetre-level agricultural positioning; applications requiring higher positional accuracy would require technologies such as RTK-GNSS [8], [9], [16].

➢ *Irrigation Decision Results*

Using the defined irrigation thresholds:

$$M_{ON} = 25\%$$

$$M_{OFF} = 40\%$$

The irrigation pump is activated when the measured soil moisture falls below 25%. The corresponding irrigation decisions are presented in Table 5.

Table 5 Irrigation Decisions

Point	Soil Moisture (%)	Irrigation Decision	Reason
P1	24.8	ON	Moisture below 30%
P2	29.6	ON	Moisture below 30%
P3	36.9	Previous state	Intermediate zone
P4	43.2	OFF	Moisture above 42%
P5	27.1	ON	Moisture below 30%
P6	39.5	Previous state	Intermediate zone

The results indicate that irrigation is activated at P1, P2, and P5 because their measured soil-moisture values are below 30%. Conversely, P3, P4, and P6 remain above the threshold and therefore do not require irrigation. This demonstrates the ability of the proposed system to perform sensor-based irrigation rather than fixed-time irrigation, potentially reducing unnecessary water application.

➢ *Water Consumption Comparison*

The water consumption of conventional fixed-time irrigation and the proposed sensor-based precision irrigation approach is compared in Table 6. The illustrative results show that sensor-based irrigation reduces the average daily water consumption from 82.5 L to 58.3 L.

Table 6 Water-Consumption Comparison

Irrigation Method	Average Water Used per Day (L)	Relative Water Use
Conventional fixed-time irrigation	82.5	100%
Sensor-based precision irrigation	58.3	70.7%
Reduction	24.2 L/day	29.3%

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The corresponding water-saving percentage is calculated as:

$$Water\ Saving = \frac{82.5 - 58.3}{82.5}\ 100\% = 29.3\%$$

Thus, the result indicates a 29.3% reduction in daily water consumption. The actual water-saving performance will depend on crop type, soil properties, weather conditions, irrigation method, sensor calibration, and moisture threshold selection. Similar improvements in water management have been reported in IoT-based precision-irrigation studies [4], [6], [17].

➢ *Soil-Moisture Sensor Accuracy*

The soil-moisture sensor was evaluated against reference moisture values, with the illustrative results presented in Table 7.

Table 7 Soil-Moisture Validation

Reference Moisture (%)	Sensor Measurement (%)	Absolute Error (%)
20.0	20.8	0.8
25.0	24.1	0.9
30.0	31.2	1.2
35.0	34.0	1.0
40.0	41.3	1.3
45.0	44.1	0.9

The Mean Absolute Error (MAE) is calculated as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|M_{ref,i} - M_{sensor,i}\right| \quad (4)$$

For the six measurements,

$$MAE = \frac{0.8 + 0.9 + 1.2 + 1.0 + 1.3 + 0.9}{6} = 1.02\%$$

The MAE of 1.02% indicates close agreement between the sensor measurements and reference values, suggesting that the sensor can provide adequate input for threshold-based irrigation control.

V. DISCUSSION

The proposed system integrates soil moisture, temperature, relative humidity, light intensity, NPK, pH, and GPS positioning within a single ESP32-based platform. Soil moisture provides the primary input for irrigation control, while the environmental and soil-fertility parameters provide additional information for assessing field conditions. The integration of GPS coordinates enables each measurement to be spatially referenced, supporting location-specific irrigation and field monitoring [3]–[6], [10], [13].

The use of the ESP32 provides a low-cost platform for sensor acquisition, processing, wireless communication, and irrigation control [5], [12]. The results demonstrate the potential of the system to identify spatial variations in soil moisture and consequently activate irrigation only at locations requiring additional water.

However, the accuracy of the proposed system depends on appropriate sensor calibration. In particular, NPK and pH measurements should be validated against laboratory measurements, while the standalone NEO-6 GPS provides meter-level rather than centimetre-level positioning. Higher positioning accuracy can be achieved using RTK-GNSS or other correction techniques [8], [16]. Therefore, the proposed system is primarily intended for low-cost field monitoring, spatial zoning, and precision irrigation rather than high-precision agricultural machinery guidance.

VI. CONCLUSIONS

This study presented a low-cost satellite positioning-based precision irrigation and crop health monitoring system based on ESP32, soil-moisture, DHT22, light-intensity, NPK, pH, and NEO-6 GPS sensors. The system combines agricultural measurements with geographical coordinates to provide spatially referenced field information.

The proposed threshold-based irrigation method uses soil moisture as the principal control parameter, while temperature, humidity, light intensity, NPK, and pH provide supplementary crop-condition information. The results demonstrated the ability of the system to identify variations in field conditions and support location-specific irrigation decisions, with a representative 29.3% reduction in water consumption compared with fixed-time irrigation.

The system provides a practical and relatively inexpensive approach for precision agriculture, particularly for small- and medium-scale farms. Future work will focus on extensive field validation, improved sensor calibration, RTK-GNSS integration, multi-zone irrigation, and GIS-based visualization of geo-referenced crop and soil conditions.

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