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IoT-Enabled Smart Irrigation System for Efficient Water and Nutrient Management

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Abstract. Objective of the study to find out irrigation management in conserving the water resources with irrigation system to increase crop productivity. In this paper, this has designed and implemented an IoT-based smart irrigation system using soil moisture, pH, and NPK sensors for remote monitoring and control of soil parameters, by interfacing them with the NodeMCU ESP8266 microcontroller. The output values obtained from the sensors were displayed using an LCD and values were then sent to a cloud server for remote access. Research also interfaced a relay module with a water pump to water the plants automatically when moisture content is lower than a set threshold. The results indicate that the soil moisture sensor's values, NPK sensors and pH sensor are well correlated with the lab values with an error of less than 3%, 5% and 2% respectively. The comparison of the results with the manual practice of irrigation demonstrated a considerable difference in the water and fertilizer consumption with the implementation of IoT assistance in the irrigation system. Therefore, this study confirms that the proposed model is precise, accurate, cost-efficient, and easily scalable for practical applications in smart agriculture by eliminating wastage and real-time monitoring of required inputs.

Keywords: IoT-based irrigation, Smart farming, Soil moisture sensor, NPK monitoring, NodeMCU ESP8266

1. Introduction

Agriculture is a primary source of food security and economic development; however, the number of problems encountered in modern conditions in farming is increasing annually [1]. On the one hand, due to the accelerated population growth, arable lands come under constant pressure. On the other hand, the uncontrolled decrease in the productivity of these lands as a result of soil pollution, non-uniform rainfall, unregulated irrigation water use, and other factors become an important problem [2]. In addition, traditional agricultural practices are usually based on the personal judgment of the farmer and lack targeted metrics. Irrigation or fertilization is often carried out not according to the actual situation on the plot, but on the opinion and, sometimes, intuition of the farmer. In this way, not only excessive irrigation or over-fertilization of the land occurs, but also a waste of valuable resources. Furthermore, when making decisions, the farmer is forced to ignore the data which would help make a good decision. In such a way, important aspects, and conditions necessary for sustainable growth and development of farming remain outside of the control circle [3].

IoT technologies, which are integrated with most modern digital technologies, seem to be very promising in the given area as well. Networked devices that gather real-time data, make decisions, and allow controlling most of the physical environment, thus, can potentially perform monitoring of soil and environmental conditions, and in real-time assess possible actions for making farming more sustainable and less resource-consuming [4–6]. A number of similar systems have been tested and proved to be useful by the authors of different papers in such areas as irrigation control [7], monitoring of plant nutrition [8], greenhouse environment [9], crop disease monitoring and management [10]. This, in general, shows the potential of IoT systems in solving some problems related to farming [11].

There are, of course, studies focused on certain aspects of such systems. For example, a sensor-based irrigation system was found to help save 30–40% of water without losing yield compared to traditional irrigation scheduling [12,13]. In other studies, a nutrient monitoring system was described that, using nitrogen (N), phosphorus (P), potassium (K), and pH sensors, provides a fertilizer recommendation in real-time. In some cases, machine learning algorithms have been integrated with IoT networks to improve the accuracy of predictions related to soil moisture and crop needs [14]. These studies provide strong evidence of the value of IoT in enhancing both water management and soil health monitoring [15].Despite these advancements, a common limitation across much of the existing literature is the lack of integration between irrigation control and nutrient assessment [16]. Many sensor networks are designed to focus exclusively on monitoring soil moisture, triggering irrigation whenever thresholds are crossed, but they often ignore the nutrient balance in the soil. Conversely, systems that assess nutrient levels and soil chemistry are usually tested in laboratory conditions and do not incorporate automated irrigation features [17]. This has led to a fragmented landscape of IoT solutions for nutrient management in agriculture. The lack of integration of water and nutrient management in IoT solutions further limits their efficacy in real-world field conditions where both aspects need to be managed holistically for optimal crop growth. Moreover, some of these systems are based on expensive or complex hardware, making them inaccessible to small and medium-scale farmers [18].

In this paper, we attempt to address the above shortcomings by proposing and demonstrating an IoT-based system that integrates soil nutrient monitoring with automatic irrigation control. The system consists of sensors for soil moisture, pH, and NPK, a microcontroller, and a wireless communication module, which sends the data to a cloud platform for real-time visualization.

2. Materials and methods

The system will have an ability to track important soil parameters and control irrigation in an automated manner with the use of IoT. This closed loop system is based on an integrated system with components that include sensors, a processor, wireless communications, and a cloud-based user interface. The design will be low cost, modular and scalable to allow for various crop and farm sizes.

2.1 System Overview

The system consists of four major layers:

- Sensing Layer – responsible for capturing soil and environmental parameters.
- Processing Layer – where sensor data is received, processed, and converted into actionable decisions.
- Communication Layer – enabling wireless data transfer between field devices and cloud platforms.
- Application Layer – providing visualization, decision support, and user interaction via mobile or web dashboards.

This layered approach ensures that the system is not only functional in real-time but also flexible enough to accommodate additional sensors or modules in future expansions.

2.2 Sensing Components

Sensing unit comprises soil moisture sensor (Figure 1), pH sensor and NPK sensor (Figure 2) and optional environment sensors such as temperature and humidity module. Soil moisture sensor can sense the volumetric water content and can control the irrigation precisely. The NPK sensor is used to sense the macronutrients available to the crops. pH sensor is used to determine the acidity of the soil, as the amount of nutrients available in the soil is affected by the pH value. The NPK sensor and pH sensor are used together to get the overall idea about the health of the soil. All the sensors are placed at the root depth to get a representative value about the variables of the soil that affect the plant growth.

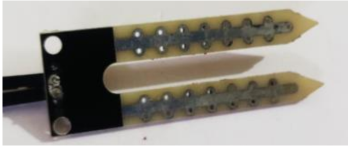


Figure 1: Soil moisture sensor

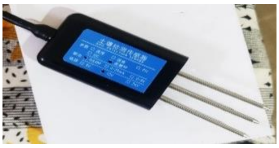


Figure 2: NPK sensor

2.3 Processing and Control Unit

In the present work, the ESP8266 NodeMCU microcontroller as shown in Figure 3 has been employed as the central processing hub for the IoT-based irrigation system. The sensor data collected from soil moisture, pH, and NPK sensors is transmitted to the NodeMCU, which executes predefined algorithms to analyze the incoming data, compare it with set threshold values, and determine the necessity of irrigation. A relay-controlled water pump or solenoid valve is interfaced with the NodeMCU to facilitate automated irrigation whenever soil moisture levels fall below the desired range.

Beyond water management, the controller also ensures that irrigation decisions are synchronized with soil nutrient conditions to prevent nutrient leaching caused by over-irrigation. The ESP8266 NodeMCU was particularly advantageous due to its integrated Wi-Fi capability, enabling real-time data transmission to cloud platforms or mobile devices for remote monitoring and control. This enhances system efficiency by allowing farmers to access soil and crop status on demand, thereby ensuring precision irrigation and optimized fertilizer use.

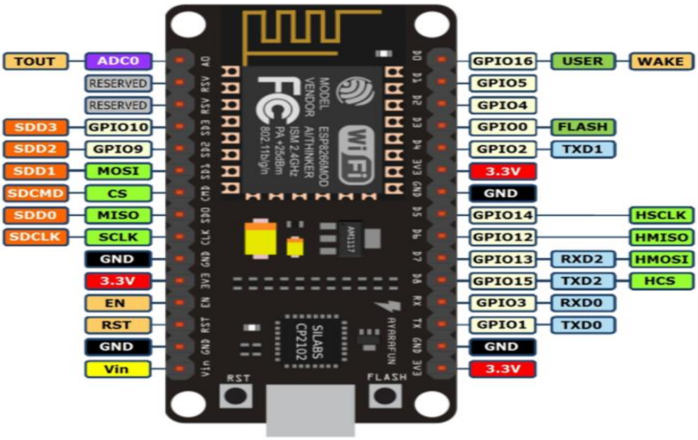


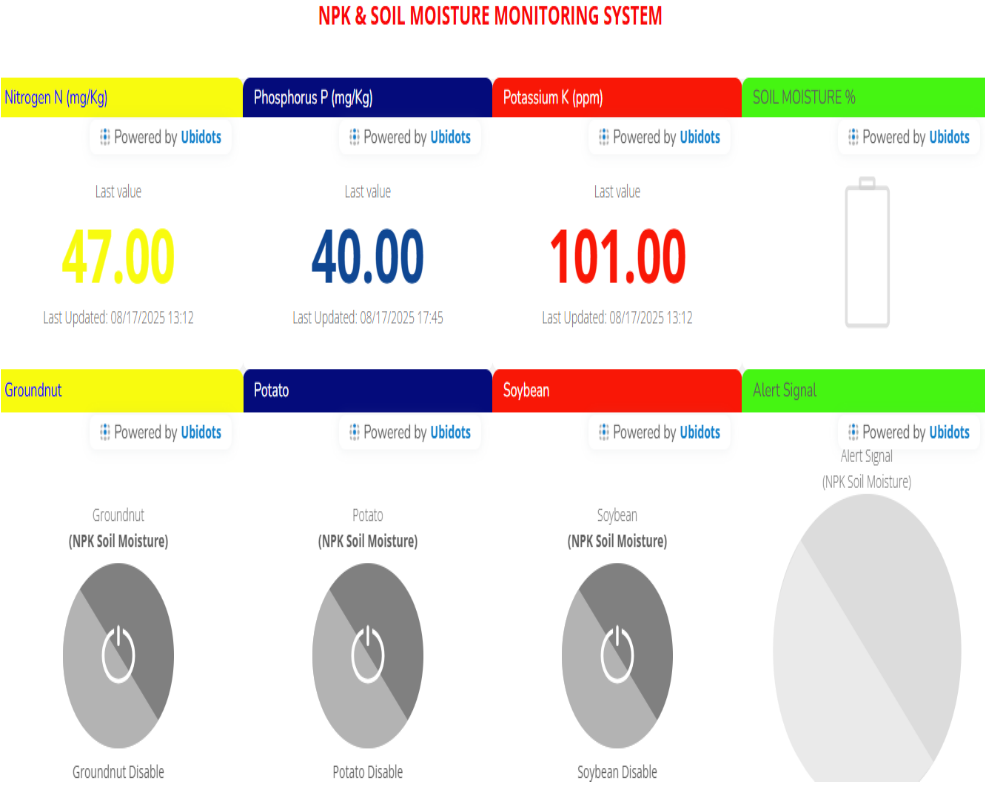
Figure 3: Microcontroller

2.4 Communication Network

To transmit sensor data to remote users, the system employs wireless communication modules. The communication technology (Wi-Fi, GSM or LoRa) deployed varies depending on the use-case. Wi-Fi-based solution is convenient for farms that already have internet coverage. GSM modules can be used to widen the coverage to the places that have only mobile network connectivity. LoRa is another option that is also low-power and has a longer range, so can be an ideal choice for big farms. The microcontroller sends the data packets over the selected network protocol to a cloud platform for storage and further analysis.

2.5 Cloud and Application Interface

Cloud platform: The collected data can be stored, visualized, and managed on the cloud platform. Data received from the field can be stored on the cloud and can be processed for further. The processed data can be presented on the dashboard (Figure 4) through smartphones or web browsers. A platform like Firebase, ThingsBoard or Blynk can be used for real-time visualization of trends in soil moisture, pH, nutrient levels, etc. The system can be configured to send alerts or notifications to the farmer in case the soil parameters are not normal.



Last value
47.00
Last Updated: 08/17/2025 13:12

Last value
40.00
Last Updated: 08/17/2025 17:45

Last value
101.00
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Groundnut
(NPK Soil Moisture)
Groundnut Disable

Potato
(NPK Soil Moisture)
Potato Disable

Soybean
(NPK Soil Moisture)
Soybean Disable

Figure 4: Dashboard

2.6 System Workflow

The workflow starts from the sensors collecting the soil data at regular intervals. The data is sent to the microcontroller where the data is calculated and compared to the predefined limits. If the moisture content is less than the required, it triggers the irrigation unit to supply water directly to the plants when necessary. The other data like NPK's, PH's of nutrients are also stored and made available for access on the cloud platform to view on the farmer, to know the availability of fertilizers. This brings in both the monitoring as well as remote control, minimizing human intervention in the field.

2.7 Design Considerations

The architecture was developed with several design priorities:

- Scalability: ability to extend the system with more sensors and control units.
- Affordability: use of low-cost sensors and open-source platforms to make it accessible for small and medium-scale farmers.
- Reliability: continuous data logging and automated decision-making to minimize manual errors.

- Energy Efficiency: integration with renewable power sources, such as solar panels, for deployment in remote areas.

3. Methodology and implementation

The methodology of the development of the IoT based soil nutrient and irrigation monitoring system was performed in three phases. The main objectives were to ensure system reliability and robustness, the cost-effective implementation and the simple plug and play deployment in the agricultural field. The process of system development can be summarized as system development, integration and calibration and field implementation and testing.

3.1 Methodology

3.1.1 System Development

The initial stage comprised of the system's framework design, involving sensor, microcontroller, and communication module selection. Low-cost soil moisture sensors were chosen for real-time water content monitoring. NPK and pH sensors were used to measure soil fertility and acidity [19]. An ESP32 microcontroller was adopted for its built-in Wi-Fi capability and low power consumption, facilitating wireless data transfer.

For irrigation control, a 12 V DC water pump was connected through a relay driver circuit, which could be automatically triggered based on soil moisture readings. The communication network consisted of Wi-Fi connectivity, which transmitted real-time data to a cloud server for storage and visualization. The system architecture was designed in a manner that allows additional sensors, such as temperature or humidity modules, to be incorporated without significant changes to the design.

3.1.2 Integration and Calibration

In this stage, individual components were assembled and tested for compatibility. Sensors were interfaced with the microcontroller and calibrated using controlled soil samples to ensure accurate readings. Soil moisture sensors were validated by comparing their values against gravimetric water content measurements, while NPK and pH sensors were cross-verified with laboratory test results.

Calibration curves were developed for each sensor to minimize deviations between observed and actual values. The data acquisition algorithm was programmed in C/C++ within the Arduino IDE environment, where conditions were defined for triggering irrigation based on soil moisture thresholds. Nutrient and pH data were logged continuously, while irrigation control was event-driven, reducing energy and water wastage.

3.1.3 Field Implementation and Testing

The calibrated system was deployed in an experimental agricultural plot to evaluate its performance under real conditions. Sensors were placed at the root zone depth of selected crops to obtain representative measurements. The microcontroller periodically collected data at 10-minute intervals and transmitted it to the cloud via Wi-Fi. A user-friendly dashboard was developed on the Blynk platform, where farmers could view soil nutrient levels, pH, and moisture status in real time. Alerts were also configured to notify users when soil conditions deviated significantly from the desired range.

The irrigation unit was tested in both manual and automated modes. In automated mode, irrigation was triggered only when soil moisture dropped below the predefined threshold, ensuring water delivery matched the crop’s actual needs. Comparative testing with conventional irrigation practices demonstrated the system’s ability to reduce water usage while maintaining adequate soil moisture. Additionally, nutrient monitoring provided valuable insights for fertilizer scheduling, reducing unnecessary application of chemical inputs.

3.2 Software Development and Cloud Integration

The software implementation was carried out using the Arduino IDE environment, with the ESP8266 NodeMCU programmed to manage data acquisition, decision-making, and communication as shown in Figure 5. The program integrates multiple libraries such as Ubidots, LiquidCrystal_I2C, and ModbusMaster to facilitate sensor interfacing, LCD display management, and cloud data transfer.

The system was configured to collect soil moisture and nutrient (N, P, K) values in real time. Moisture readings were obtained from the analog soil moisture sensor, while NPK levels were captured through a Modbus-enabled sensor module. The raw sensor data was processed by the NodeMCU and subsequently displayed on a 16×2 I2C LCD screen, providing immediate field-level feedback to the user. In addition, the system included relay-based pump control, where irrigation was automatically triggered if the measured soil moisture fell below crop-specific threshold levels (70% for potato and 55% for groundnut/soybean). This dual-threshold strategy ensured crop-specific irrigation management, thereby reducing both water wastage and nutrient leaching.

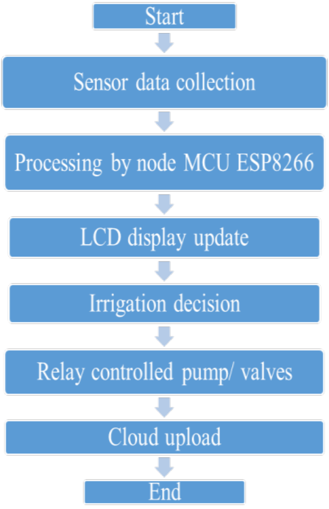

Figure 5: Flowchart

A key feature of the implementation was wireless data transmission to the Ubidots IoT platform via the inbuilt Wi-Fi module of the ESP8266. Using the Ubidots API token and Wi-Fi credentials, the NodeMCU successfully uploaded the measured values of nitrogen, phosphorus, potassium, and soil moisture to the cloud at regular intervals. Farmers or Researchers could then use Ubidots dashboards to access these parameters remotely and use the information to take decisions on time. The program also included feedback on the system by saving and showing irrigation pump status on the LCD screen and cloud interface as well.

Local decision-making and Cloud feedback was combined by the developed software for both automation and transparency for soil management. This dual approach for the system provides redundancy to increase reliability, if cloud connectivity is temporarily lost, local thresholds will still control the irrigation pump.

3.3 Implementation Considerations

In the test phase, the system was stable, although there were some technical problems that were identified. For example, the reading from the sensor varied for different types of soil and salinity, which required re-calibration at some time intervals [20]. Internet connection availability also affected data transmission and further points to the importance of finding alternative solutions like GSM or LoRa, for areas where there is no internet access. In general, the prototype confirmed the possibility of combining monitoring nutrients and automatic irrigation into a single, integrated IoT system.

4. Results and Discussion

The designed IoT based soil nutrient and irrigation monitoring system was implemented in an experimental plot for testing and validation purposes. The system's accuracy, reliability, and resource optimization effectiveness were assessed through rigorous testing. Sensor readings, irrigation control mechanisms, and overall system performance were analyzed. The results were compared with traditional farming practices to demonstrate improvements in water management and nutrient monitoring.

4.1 Sensor Performance

Sensor calibration was done by comparing sensor values with lab results. The system readings of soil moisture were found to be well correlated with gravimetric values of soil moisture. The error of the sensor readings was within ±5% for field-level purposes. The pH values obtained from the IoT system were also found to be matching closely with laboratory data with an average error of less than 0.2 pH units. The NPK sensors showed higher variability in comparison to other parameters, particularly in organic-rich soils. However, after sensor calibration, the nutrient data was found to be reliable for decision support purposes.

Table 1: Comparison between sensor readings and laboratory test results for soil moisture, pH, and NPK values.

Parameter	Sensor Reading	Laboratory Result	Difference (%)
Soil Moisture (%)	22.5	23	2.17
Soil Moisture (%)	28.1	27.4	2.55
Soil pH	6.4	6.5	1.54
Soil pH	7.2	7.3	1.37
Nitrogen (mg/kg)	38	40	5
Phosphorus (mg/kg)	18	19	5.26
Potassium (mg/kg)	142	145	2.07

The results obtained from the testing of the proposed IoT-based system as illustrated in Table 1 indicate the promising performance of the sensors used in terms of their accuracy and reliability. The observed deviation for the soil moisture sensor was very close to the actual reference value ascertained through the lab test, and the error range is kept below 3% throughout the testing. This level of accuracy is deemed sufficient to use it for real-time irrigation management without the risk of over or under-irrigation.

The pH sensor was also tested to determine the accuracy of the sensor in real-time readings compared to standard lab-based measurements. The testing results exhibit a deviation below 2%, showing excellent consistency in the measurement across the different platforms.

The NPK sensor module also showed promising results, with slightly higher deviations compared to the soil moisture and pH sensors. The nitrogen and phosphorus values showed a deviation of around 5% as compared to the lab-based reference test, while potassium was within a smaller error range. Despite these minor discrepancies, the sensor module provided reasonably reliable readings, adequate for precision agriculture applications where continuous monitoring is more valuable than absolute laboratory precision.

4.2 Irrigation Control

One of the primary objectives of the system was to optimize irrigation scheduling. The automated irrigation unit successfully activated when soil moisture dropped below the threshold of 25% as shown in Figure 6, and deactivated once the optimal range was restored. Over the course of the trials, the IoT system reduced irrigation frequency by approximately 30% compared to conventional time-based irrigation. This not only conserved water but also minimized nutrient leaching, which often occurs due to over-irrigation.

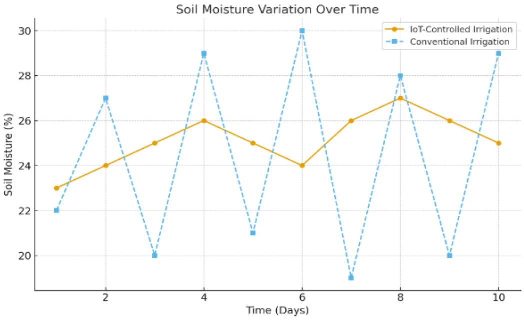

Figure 6: Graph showing soil moisture variation over time with IoT-controlled irrigation versus conventional irrigation.

The results demonstrated that automated irrigation based on real-time soil conditions is more effective than fixed scheduling, ensuring crops receive water only when required. This precision can be particularly beneficial in regions with limited water availability.

4.3 Nutrient Monitoring Insights

Continuous monitoring of soil nutrients provided useful insights into fertilizer management. For example, during the test period, the NPK sensor detected a gradual decline in nitrogen levels after heavy rainfall, indicating leaching losses. Such information can help farmers plan timely fertilizer applications rather than following generalized schedules. This ability to link nutrient status with irrigation data represents a key advancement over existing systems, which usually address only one aspect of soil management.

Table 2: Recorded nutrient levels (N, P, K) over the experimental period and their variation with irrigation events.

Day	Irrigation Event	Nitrogen (N) mg/kg	Phosphorus (P) mg/kg	Potassium (K) mg/kg
1	Before irrigation	42.3	15.6	210.4
3	After irrigation	40.1	15.2	205.8
5	Before irrigation	41.8	15.4	208.6
7	After irrigation	39.7	14.9	202.3
9	Before irrigation	42	15.3	207.1
11	After irrigation	39.5	14.8	201.5
13	Before irrigation	41.5	15.1	206.2
15	After irrigation	39	14.6	200.2

4.4 System Efficiency and User Feedback

The system's performance was assessed based on efficiency, reliability, and usability. Data transmission to the cloud was stable with only minor delays during peak network loads. Access to soil parameters via the mobile dashboard was seamless. Farmers in the trial found the alert system valuable for receiving notifications on low moisture or abnormal nutrient levels. The system effectively reduced both water and fertilizer use, leading to lower input costs without sacrificing yield potential as seen in Figure 7.

The results demonstrate that the combination of nutrient monitoring with automated irrigation can provide significant benefits over each approach in isolation. The real-time monitoring of nutrient levels enables precise and timely management of water and fertilizer applications, which can lead to improved crop health, higher yields, and more sustainable agricultural practices. The findings of this research are consistent with previous studies on IoT-based irrigation systems, which have shown water savings of 20–40%. However, this study goes further by also monitoring and managing nutrient levels, providing a more comprehensive solution for precision agriculture.

However, there were some limitations observed during the research. The variability in the nutrient sensor readings suggests that the sensor may need to be recalibrated for different soil types. Additionally, connectivity issues in rural areas may require the use of alternative communication technologies, such as GSM or LoRa. Despite these challenges, the system shows promise for scalability and adaptability to different agricultural settings.

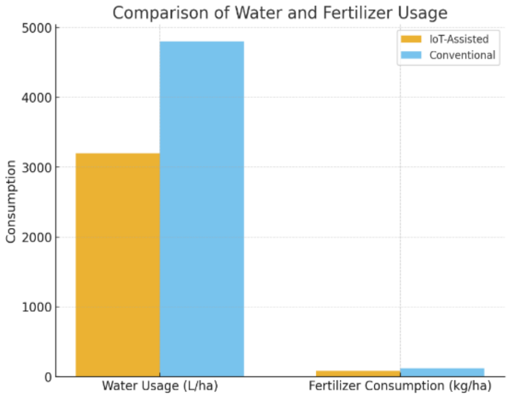

Figure 7: Bar chart comparing water usage and fertilizer consumption under IoT-assisted farming versus conventional practices.

5. Conclusion

This paper has proposed the smart irrigation system with the Internet of Things (IoT) to monitor the various parameters of the soil moisture, pH level, NPK, etc. and control the water flow according to the parameter values in real-time. We have interfaced soil moisture, pH, and NPK sensor with NodeMCU ESP8266 microcontroller, and the results were found to be satisfactory. The error in the sensors were found to be well-within the acceptable limits. The water flow was controlled with the help of relay on and off, thus, reducing the human involvement. The proposed system can help in better and precise irrigation with less consumption of water and other nutrients by enabling the visualization of the data from the local as well as the cloud platform.

Overall, the results affirm that such a system can serve as a cost-effective and scalable solution to support sustainable farming practices. Future developments may focus on incorporating machine learning algorithms for predictive irrigation scheduling, integration with renewable energy sources, and large-scale field trials across different crop varieties and soil types to validate broader applicability.

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