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Smart Nutrition Management: an IoT Solution for Sustainable and Precision Agriculture

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Abstract

The swift implementation of hydroponic gardening as a soilless agricultural technique has underscored the essential requirement for meticulous nutrient control to guarantee plant vitality and yield. Conventional manual monitoring frequently results in discrepancies in nutrient levels, potentially causing crop failure. This research tackles these problems by creating an automated monitoring system that incorporates Internet of Things (IoT) technologies. The suggested system employs pH sensors and analogue Total Dissolved Solids (TDS) sensors to continually monitor water acidity, Electrical Conductivity (EC) values, and the concentration of dissolved solids in the nutrient reservoir. A specialised mechanism is included to automate the agitation of AB Mix nutrition, guaranteeing a uniform distribution of minerals. The technology entails the integration of these sensors with a microcontroller to facilitate real-time data transmission and remote monitoring. The findings demonstrate that the technology markedly improves the accuracy of nutrient administration and reduces human error in sustaining optimal growth circumstances. This technology offers a dependable solution for real-time tracking, mitigating the risk of planting failures and enhancing resource efficiency in smart agricultural settings. This system functions as a pragmatic execution of automated agriculture, providing a scalable framework for both industrial and community-oriented hydroponic projects. This study implements an autonomous IoT-based nutrient monitoring and control system for hydroponic agriculture, integrating pH, TDS, temperature, humidity, and solution volume sensing with a custom mobile application. The system was validated across two consecutive cultivation cycles, demonstrating its capability to detect nutrient degradation and solution instability, thereby supporting timely nutrient management decisions and reducing manual intervention.
Keywords: *Hydroponics, Internet of Things, pH Sensor, Smart Agriculture, TDS Sensor.*

Introduction

The agricultural sector is at a critical juncture where traditional farming practices must evolve to meet the rising demands of a growing global population while addressing challenges such as resource depletion, environmental degradation, and climate change. Smart agriculture, also known as precision agriculture, has emerged as a transformative approach that employs advanced technologies to enhance farming operations, boost productivity, and promote sustainable agricultural practices. This revolution focuses on the integration of Internet of Things (IoT) technology, enabling real-time monitoring, data-driven decision-making, and automated control systems that significantly alter agricultural management of crops and resources.

Soil nutrient management is essential for optimal crop cultivation, as soil nutrients directly influence plant growth, crop yield, and overall agricultural productivity. Traditional soil analysis methods, marked by manual sampling and laboratory testing, are laborious and time-consuming, resulting in delayed data that may inadequately reflect the dynamic characteristics of soil conditions. Traditional techniques often produce inadequate fertiliser application, leading to nutrient deficiencies that compromise agricultural productivity or excessive fertilisation that causes environmental harm and economic loss. The need for continuous, real-time evaluation of soil nutrient levels has become increasingly clear as farmers strive to implement precision agriculture techniques that improve resource efficiency and maintain environmental sustainability.

Recent advancements in sensor technology, wireless communication systems, and data analytics have enabled the development of intelligent soil monitoring systems that provide farmers with swift and accurate information about soil nutrient levels. IoT-based soil nutrient analysis systems have demonstrated significant potential in revolutionising agricultural practices by enabling continuous monitoring of critical soil parameters, including nitrogen (N), phosphorus (P), and potassium (K) levels, along with other essential factors such as soil moisture, pH, and temperature. These systems utilise various sensing technologies and communication protocols to collect soil data, transmit it to cloud-based platforms for processing and analysis, and deliver actionable insights to farmers through user-friendly interfaces available on mobile devices or internet applications.

The implementation of advanced nutrition monitoring systems in agriculture addresses various critical challenges faced by modern farmers. These devices provide real-time information into soil nutrient variations, allowing farmers to make informed decisions about the timing and amount of fertiliser application. Studies demonstrate that IoT-based soil monitoring systems can significantly improve fertilisation efficiency by administering nutrients only when required and in appropriate quantities [13]. Secondly, continuous monitoring enables the prompt detection of nutrient deficiencies or imbalances, allowing for preemptive measures before negative impacts on crop yield occur. Third, the data collected by these systems may be integrated with predictive analytics and machine learning algorithms to forecast crop requirements, recommend suitable crops based on soil conditions, and optimise irrigation schedules [2][4].

The architecture of IoT-based soil nutrition monitoring systems often consists of multiple interconnected components that work together to deliver full soil management solutions. Sensor nodes equipped with various soil sensors are deployed in agricultural fields to measure critical parameters including NPK levels, soil moisture, temperature, pH, and electrical conductivity. These sensors employ many measurement techniques, including electrochemical methods, colorimetric analysis, and spectroscopic approaches [9][23]. The collected data is then transmitted using wireless communication protocols such as ZigBee, LoRa, or cellular networks to gateway devices or straight to cloud servers for storage and processing [7][8]. Advanced data processing techniques, including machine learning algorithms and artificial intelligence models, are employed to evaluate the collected data, identify patterns, and generate significant recommendations for farmers [22].

Wireless Sensor Networks (WSN) are crucial for enabling dispersed soil monitoring across vast agricultural areas. Soil nutrient monitoring systems based on Wireless Sensor Networks (WSN) utilise several sensor nodes systematically deployed throughout agricultural terrain to produce a comprehensive spatial depiction of soil conditions [7][16]. This distributed sensing technique provides farmers with comprehensive insights into soil variability across many zones of their farms, enabling site-specific management strategies that optimise resource allocation. The integration of mobile sensor nodes has enhanced the flexibility and range of these monitoring systems, enabling the dynamic repositioning of sensors based on crop growth phases or specific monitoring requirements [16].

The capacity for real-time monitoring is a considerable advantage of IoT-based soil nutrition systems over traditional soil testing methods. Studies indicate that continuous monitoring systems can detect rapid changes in soil nutrient availability caused by factors such as precipitation, irrigation, or microbial activity, which periodic laboratory tests may miss [3][13]. This temporal resolution enables farmers to promptly adjust to varying soil conditions, altering their fertilisation strategies to maintain optimal nutrient levels throughout the producing season. Furthermore, the accessibility of real-time data facilitates the implementation of automatic irrigation and fertilisation systems that can independently adapt to soil conditions without requiring constant human supervision [14][35].

The integration of soil nutrient evaluation with crop advising systems represents a significant advancement in precision agriculture. By analysing soil nutrient profiles in conjunction with environmental variables and historical crop performance data, these sophisticated algorithms can predict crop compatibility and recommend optimal crops for certain soil conditions [2][4]. Machine learning algorithms, employing extensive datasets of soil characteristics and crop yields, can identify complex relationships between soil parameters and crop performance, providing farmers with data-driven insights for crop selection and rotation planning [18]. The integration of soil analysis and predictive analytics allows farmers to maximise economic returns while maintaining soil health and sustainability.

Environmental sustainability is a vital consideration in modern agricultural practices, with intelligent nutrition monitoring systems significantly contributing to the reduction of farming's environmental impact. Precision fertilisation, enabled by real-time soil monitoring, reduces nutrient runoff into aquatic ecosystems, hence alleviating the risk of eutrophication and water contamination [11]. By administering fertilisers just when required and in appropriate quantities, these systems reduce greenhouse gas emissions associated with excessive nitrogen fertilisation while concurrently lowering output costs for farmers. Preserving optimal soil nutrient levels promotes healthier soil ecosystems, enhances beneficial microbial populations, and augments long-term soil fertility.

The use of colorimetric methods for soil nutrient analysis has attracted attention as a cost-effective alternative to expensive laboratory equipment. Colorimetric methods utilise chemical reagents that produce colour changes in response to certain soil nutrients, with the extent of colour alteration corresponding to nutrient levels [9]. These technologies can be integrated with image processing techniques and smartphone cameras to provide economical, field-deployable solutions for rapid soil nutrient assessment. A recent study demonstrated the feasibility of utilising colour analysis algorithms to accurately predict NPK levels, hence enabling improved soil testing for smallholder farmers without access to contemporary laboratory facilities [21].

Data visualisation and user interface design are crucial for the effectiveness of intelligent nutrition monitoring systems. Agriculturists necessitate clear and concise presentations of complex soil data to enable timely and informed decision-making. Modern IoT solutions have interactive dashboards, graphical representations of temporal trends, spatial heat maps depicting nutrient distribution across fields, and automated alert systems that notify farmers when soil parameters fall outside ideal limits [3][17]. Mobile applications have emerged as primary interfaces for these systems, allowing farmers to access real-time soil data, receive guidance, and run automated systems from any location at any time.

The economic viability of implementing smart nutrition monitoring systems is a critical consideration for extensive adoption in the agricultural sector. Despite the significant initial investment in sensors, communication infrastructure, and cloud services, research demonstrates that the long-term benefits, such as increased crop yields, reduced fertiliser costs, and improved resource efficiency, can provide considerable returns on investment [18][24]. The progress of cost-effective sensor technology and the availability of open-source IoT platforms have markedly improved the accessibility of these systems for farmers from diverse economic backgrounds. The ability to utilise data-driven insights to reduce crop failures and improve production planning promotes increased economic stability for agricultural businesses.

The incorporation of additional smart farming technology produces synergistic effects that amplify the benefits of nutrition monitoring systems. The integration of soil nutrient monitoring with automated irrigation systems, weather monitoring stations, and crop health surveillance equipment creates a comprehensive farm management ecosystem that improves all aspects of agricultural productivity [19][36]. Integrating meteorological forecasts could predict how impending rainfall may affect soil nutrient availability, allowing for proactive adjustments to fertilisation schedules. The correlation between soil nutrient data and crop health imaging helps clarify the influence of nutrient levels on plant growth and development.

The utilisation of machine learning and artificial intelligence in soil nutrient management has opened new avenues in predictive agriculture. Advanced algorithms can analyse historical soil data, meteorological patterns, crop performance records, and other relevant factors to forecast future nutrient requirements, optimise fertilisation strategies, and identify potential soil-related problems before they arise. Deep learning models have proven effective in identifying complex, non-linear relationships between diverse soil factors and crop outcomes that may be overlooked by traditional statistical techniques. These AI-driven algorithms continuously incorporate new data, improving their accuracy and recommendations over time.

Despite the significant potential of intelligent nutrition monitoring systems, certain obstacles must be addressed to encourage broader adoption. The calibration and maintenance of sensors can be demanding, particularly in challenging agricultural environments where sensors face dust, moisture, and mechanical strain. Ensuring long-term sensor precision and reliability is an ongoing task that requires attention to sensor design, protective enclosures, and regular calibration protocols [10][23]. The energy requirements of sensor nodes in remote agricultural regions necessitate careful consideration of energy-efficient designs and renewable energy sources, such as solar panels, to ensure continuous operation without frequent battery replacements.

As agricultural systems become increasingly interconnected and dependent on data, concerns about data security and privacy have emerged. Agricultural data, including soil conditions, crop performance, and management tactics, represents crucial intellectual property that farmers must protect from unlawful access or exploitation. Implementing robust cybersecurity standards, including data encryption, secure authentication techniques, and access controls, is essential for cultivating confidence in IoT-based agricultural systems [41]. Furthermore, farmers seek thorough understanding and supervision regarding the collecting, storage, sharing, and utilisation of their data by various stakeholders within the agricultural value chain.

Obstacles in standardisation and interoperability impede the smooth integration of many IoT devices and platforms within agricultural settings. The agricultural IoT ecosystem consists of sensors, communication protocols, data formats, and software platforms from various manufacturers and developers, often demonstrating restricted compatibility. Establishing industry standards for agricultural IoT systems, including standardised data formats and communication protocols, is crucial for enabling farmers to incorporate components from diverse manufacturers and assuring long-term system sustainability and upgradability.

The development of intelligent fertilisation recommendation systems that utilise soil nutrient monitoring data represents a rational evolution of these technologies. Advanced techniques can ascertain precise fertiliser needs by evaluating forecast crop yields, current soil conditions, expected nutrient uptake rates, and environmental factors, rather than only reporting existing nutrient levels [11][36]. These recommendation algorithms can account for the complex interactions among different nutrients, the impact of soil pH on nutrient accessibility, and the timing of fertiliser administration concerning crop growth stages. By automating the complex calculations required for fertiliser management, these technologies make precision agriculture methods accessible to farmers without requiring extensive agronomic expertise.

This study presents an innovative smart nutrition monitoring system for agriculture, employing IoT technology to meet the critical need for real-time, accurate soil nutrient management in modern farming techniques. The proposed system integrates advanced sensor technologies, wireless communication networks, cloud-based data processing, and cognitive analytics to provide farmers with actionable insights for improving crop nutrition and increasing agricultural output. This system aims to improve sustainable, efficient, and economically viable agricultural practices in the digital farming era through continuous monitoring of soil NPK levels and other critical factors, coupled with data-driven recommendations and automated control functionalities.

While several research have investigated IoT-based monitoring systems for smart agriculture, the majority of current implementations emphasise data collecting and visualisation, neglecting autonomous nutrient regulation and multi-cycle system validation. This work fills the gap by creating an IoT-based hydroponic fertiliser management system that combines real-time monitoring with automated AB Mix nutrient control and mobile application oversight. The suggested system is evaluated through two successive planting cycles, allowing for the detection of nutrient degradation situations in which supplementary fertilisation becomes useless. This method offers pragmatic decision assistance for hydroponic nutrient administration and improves the dependability of IoT applications in intelligent agriculture.

Research Methods

2.1. Software and Hardware Design

The main components required for this research are a hydroponic frame, nutrient storage tank, nutrient circulation system, ESP32, ultrasonic sensor, TDS sensor, pump, soldering iron, 220-volt AC cable, tin, and a 5V USB adapter. The hydroponic system construction process involves several steps, as illustrated in the flowchart in the following figure.

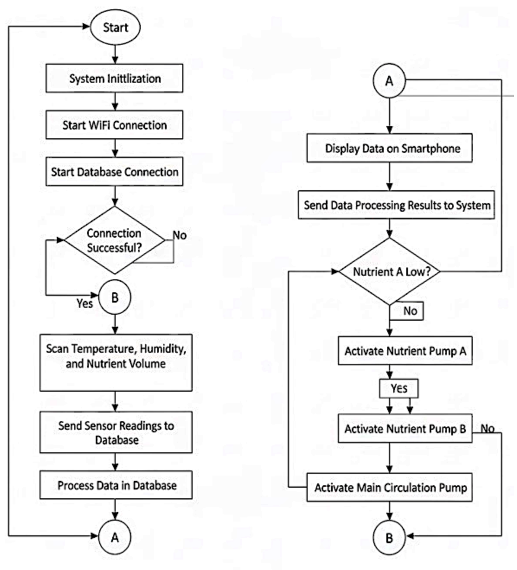

Figure 1. Flow diagram of the manufacturing process

Based on the flowchart above, the process begins with the ESP32 microcontroller establishing a Wi-Fi connection. Once connected, the controller reads data from the DHT22 sensor (temperature and humidity), the ultrasonic sensor (water volume), and the TDS sensor (nutrient levels). These readings are then transmitted to a database and displayed on the designated application. If the monitoring data indicates a deficiency in either Nutrient A or B, the system will trigger the respective nutrient pump. Additionally, the system is designed to allow manual activation of the circulation pump via the app, enabling efficient remote management.

Results and Discussion

The outcomes obtained from this tool design are illustrated in Figure 3. Figure 2 illustrates the three-dimensional design of the circuit schematic. The monitoring tool we developed can be utilised for hydroponic oversight. Figure 4 presents a representation of the APK we developed. The Results section is an essential element of the research piece, showcasing the primary findings obtained from the study, including the outcomes of hypothesis testing. The utilisation of tables and figures (e.g., charts, graphs) is highly recommended to graphically present the facts clearly and effectively.

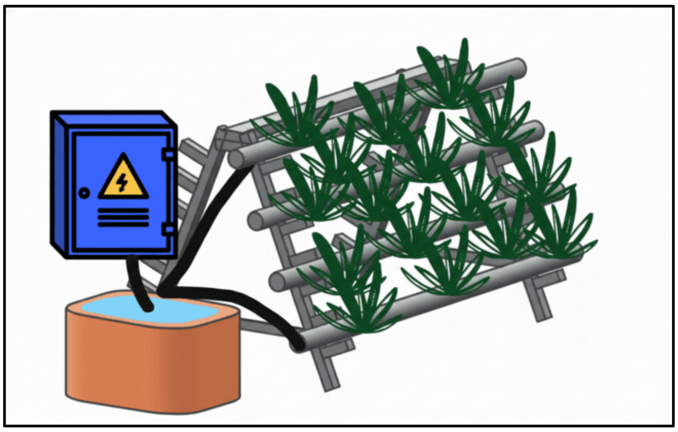

Figure 2. Hydroponic Design

Figure 3. Tool Implementation

The hydroponic planting method is equipped with two sensors: a DHT11 sensor and an ultrasonic sensor. The DHT11 sensor is used to monitor the temperature and humidity of the plants. Research has shown that the measurement error of the DHT11 sensor is 3.12%. If the detected temperature is less than the set value, the system will automatically supply water to the hydroponic plants. The advantage of requiring only one signal (GIS), in addition to the 5V line and ground. Ultrasonic sensors can detect the distance of an object by emitting ultrasonic waves (40 kHz) and then detecting the reflections. Similarly, for humidity, if the nutrient solution measured by the sensor is less than the predetermined standard value, the system will automatically add nutrient solution. The following readings on the serial monitor are shown in Figure 4 below:

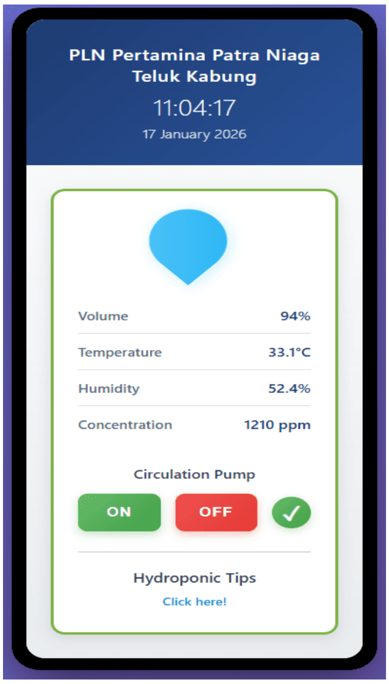

Figure 4. Hydroponic monitoring application display

Table 1. Monitoring System Observation Results

No	Observed Aspect	Set Parameters	First Planting (M1-M5)	Second Planting (M1-M5)
1.	Temperature (°C)	10–40°C	24, 28, 25, 26, 29	27, 28, 29, 27, 25
2.	Volume (%)	40–100%	98, 91, 87, 76, 69	58, 44, 32, 99, 93
3.	Humidity (%)	50–85%	58, 56, 63, 74, 78	76, 65, 83, 59, 63
4.	Solution Concentration (ppm)	700–1400 ppm	1318, 1212, 1298, 1000, 789	1300, 1229, 457, 1000, 789
5.	pH Level	5–8	6.6, 6.8, 6.6, 6.7, 6.7	6.8, 6.7, 6.7, 6.8, 6.6

The observations in the table indicate that by the third week of the second planting, or the eighth week, the solution concentration diminished, signifying that the nutrients were no longer effective. Nonetheless, owing to temperature and humidity conditions, the water in the primary tank (tub) became green. No quantity of nutrients introduced could alter the concentration of the solution. The water was murky and green, necessitating a change. We can ascertain that our monitoring system is functioning effectively. The results of this study demonstrate that the proposed IoT-based hydroponic nutrient monitoring system is capable of continuously tracking key environmental and nutritional parameters, including temperature, humidity, solution volume, pH, and nutrient concentration, across two consecutive planting cycles. The integration of real-time sensing with autonomous nutrient regulation enables the system to respond dynamically to changes in nutrient conditions, thereby reducing reliance on manual intervention.

Compared with the IoT-based soil and nutrient monitoring system proposed by Pyingkodi et al. [1], which primarily focuses on real-time data acquisition and visualization, the system developed in this study extends functionality by incorporating automatic AB Mix nutrient control. While Pyingkodi et al. emphasised monitoring accuracy, the present work highlights practical decision-making capability, particularly in identifying conditions where additional nutrient input no longer improves solution quality. This distinction is critical for hydroponic applications, where nutrient imbalance can rapidly affect plant growth.

Furthermore, the findings align with the study by Kamelia et al. [3], who reported that real-time monitoring significantly improves the responsiveness of smart farming systems. However, unlike their system, which relies on external interpretation of sensor data, the proposed system integrates monitoring with direct actuation through nutrient pumps, enabling immediate corrective actions. This integrated approach enhances operational efficiency and reduces delays between data acquisition and system response. In comparison with Patil et al. [13], who developed an IoT-based soil nutrient detection system focusing on NPK measurement, this research places greater emphasis on hydroponic nutrient stability over time rather than single-point nutrient detection. The multi-week monitoring across two planting cycles revealed a critical condition in which nutrient concentration declined despite additional fertilization, indicating solution degradation. This observation supports the importance of continuous monitoring, as also suggested by Shylaja and Veena [7], who emphasized the role of temporal data resolution in improving nutrient management accuracy.

The decline in nutrient effectiveness observed during the second planting cycle highlights a practical limitation often overlooked in IoT-based hydroponic studies. While most previous research assumes that nutrient replenishment directly restores optimal conditions, the results of this study show that water quality degradation, indicated by murky and green solution appearance, can prevent effective nutrient absorption. This finding reinforces the need for intelligent systems that not only regulate nutrient dosage but also support decisions for complete solution replacement.

Overall, the discussion confirms that the proposed system contributes to smart agriculture by moving beyond passive monitoring toward autonomous nutrient management validated under real cultivation conditions. By combining real-time sensing, automated control, and mobile application-based supervision, the system provides a reliable and practical framework for small-scale hydroponic farming, consistent with the objectives of precision agriculture and sustainable resource management

Conclusion

The IoT-based AB Mix Nutrient Monitoring System for Hydroponic Plants was developed to assist the PLN Berseri program, wherein the system autonomously regulates the nutrition of hydroponic plants. Additionally, sensor measurements like acidity, nutrient concentrations, temperature, and humidity are tracked via a customised application. All components are amalgamated to streamline the monitoring procedure and yield superior hydroponic plants through a fully automated system.

Conclusion

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