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Automated Irrigation and Nutrient Fertilization System for Sustainable Agriculture

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Abstract

This study presents an automatic irrigation and fertilization system designed to provide a smart, real-time, and cost-effective solution for modern agriculture. The system integrates soil moisture sensors, an Arduino Uno microcontroller, a water pump, and fertilizer dispensing valves to maintain optimal soil conditions. Soil moisture is continuously monitored, and irrigation is activated only when required, reducing water wastage and ensuring proper hydration. A programmed fertilization module delivers precise nutrient quantities, minimizing human error and preventing over-fertilization associated with conventional manual practices. A functional prototype was developed and evaluated under controlled conditions. Experimental results showed nearly a 40% reduction in irrigation cycles compared to manual methods, demonstrating significant improvement in water-use efficiency. Fertilizer distribution was more uniform, leading to healthier root systems, improved soil structure, and enhanced crop quality. Data analysis revealed a strong correlation between automated water–nutrient management and improved plant growth.

The study further evaluates system affordability, scalability, and suitability for small and medium-scale farmers, particularly in rural and resource-limited regions. The modular and low-cost design allows customization based on crop type, soil characteristics, farm size, and climatic conditions. Future enhancements include integration of IoT, GSM modules, and mobile applications for remote monitoring and predictive analysis.

Keywords: *Automated irrigation system, Precision agriculture, Sustainable agriculture, Water conservation, Crop yield optimization, Smart farming, Agriculture automation.*

Introduction

Global food security depends on agriculture, which continues to be the foundation of many developing economies. Adopting contemporary technologies that improve productivity, reduce resource waste, and optimize crop management techniques is becoming more and more necessary due to the fast population growth and mounting pressure on agricultural productivity. Conventional farming methods, especially those pertaining to fertilization and irrigation, frequently rely on periodic estimation and manual observation. In addition to being time-consuming, these methods are often inaccurate, which results in excessive water use, nutrient imbalances, and decreased crop yield. In recent years, the integration of automation in agriculture—often referred to as "smart farming" or "precision agriculture"—has emerged as a transformative solution to these challenges. . Farmers can monitor soil conditions and more precisely control resource distribution with the help of technologies like microcontrollers, sensors, and automated control systems. Many farmers, particularly in rural areas, continue to use labour-intensive and ineffective irrigation techniques despite advances in technology. Inadequate irrigation continues to lead to waste and soil degradation, and water scarcity has emerged as a major worldwide concern. In a similar vein, fertilizers are frequently manually applied in excessive or insufficient amounts, which can lead to environmental contamination, plant stress, or nutrient leaching. These problems underscore the need for a contemporary solution that can use real-time data to automate the fertilization and irrigation processes.

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Even small-scale farmers with little technical experience can implement such automation thanks to the affordable, adaptable, and effective platform that an Arduino-based system offers. The inefficiency of traditional irrigation and fertilization techniques, which mainly rely on human judgment and frequently neglect to take into account variations in soil moisture levels and crop nutrient requirements, is the issue this study attempts to address. Climate, labour availability, and farmer experience all influence manual monitoring, which is unreliable. Crops may thus receive too much or too little water and nutrients, which would have a detrimental effect on soil health and productivity. A system that can autonomously measure soil parameters, make prompt decisions, and control resource supply without constant human intervention is required to meet these challenges.

The study has four goals. The first step is to create and install an Arduino-controlled irrigation system that uses real-time soil moisture readings to trigger water flow. The second is to create an automated fertilization module that applies the necessary nutrients according to soil conditions or at predetermined intervals. Third, to assess how well the system uses resources, enhances plant growth, and minimizes manual labour. The study's final goal is to evaluate the viability, affordability, and long-term viability of using microcontroller-based automation in agricultural settings.

This study is important because it has the potential to make a substantial contribution to sustainable farming methods. Farmers can guarantee that crops receive the proper amount of water and nutrients at the right time, resulting in better growth, higher yields, and healthier soil, by automating irrigation and fertilization. The system makes cutting-edge technology accessible even to farmers in remote and low-income communities by providing a workable and cost-effective solution to typical agricultural problems. Additionally, by cutting down on water waste and stopping the improper use of chemical fertilizers, it encourages environmental conservation. Such intelligent systems have the potential to significantly contribute to the long-term transformation of traditional agriculture into a more productive, data-driven, and environmentally responsible sector.

Hardware Components Description

1. **Arduino Uno Microcontroller**

The Arduino Uno is the central control unit of the proposed automatic irrigation and fertilization system. It is based on the ATmega328P microcontroller and operates at 5 V with a clock frequency of 16 MHz. The Arduino Uno is responsible for acquiring data from the soil moisture sensor, processing the sensor readings, and controlling the DC water pump and fertilizer dispensing solenoid valve through relay modules. Its advantages include low cost, ease of programming using Arduino IDE, availability of digital and analog I/O pins, and suitability for real-time agricultural automation applications.

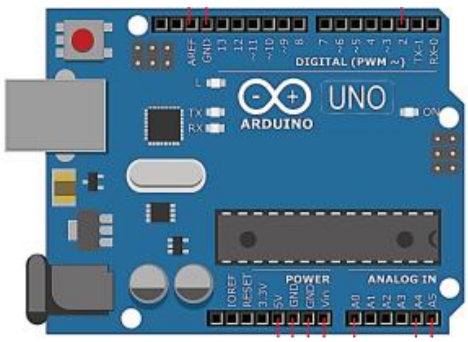

Fig: Arduino UNO

2. **Soil Moisture Sensor**

The soil moisture sensor is used to measure the volumetric water content of the soil. It operates on the principle of variation in electrical resistance with soil moisture levels. When the soil is dry, the sensor outputs a higher resistance value, whereas wet soil produces lower resistance. The sensor provides an analog output that is read by the Arduino Uno through an analog input pin. Based on predefined threshold values, the system determines whether irrigation is required.

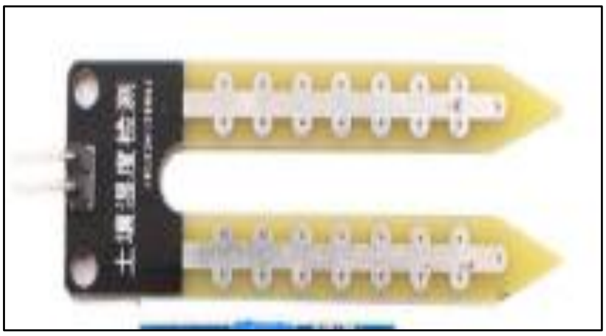

Fig: Soil moisture sensor

3. **DC Water Pump**

A DC water pump is employed to supply water to the soil when irrigation is required. The pump is controlled through a relay module interfaced with the Arduino Uno. When the soil moisture level falls below the threshold, the Arduino activates the relay, allowing current to flow through the pump and initiate irrigation. Once the desired moisture level is achieved, the pump is automatically turned off. This ensures efficient water usage and prevents over-irrigation.

4. **Block Diagram of the System**

The block diagram of the proposed automatic irrigation and fertilization system illustrates the interaction between the sensing, processing, and actuation units. The soil moisture sensor continuously monitors soil conditions and sends data to the Arduino Uno microcontroller. Based on the programmed logic and threshold values, the microcontroller controls the relay module, which in turn operates the DC water pump and fertilizer dispensing mechanism. This closed-loop system enables automatic decision-making without human intervention.

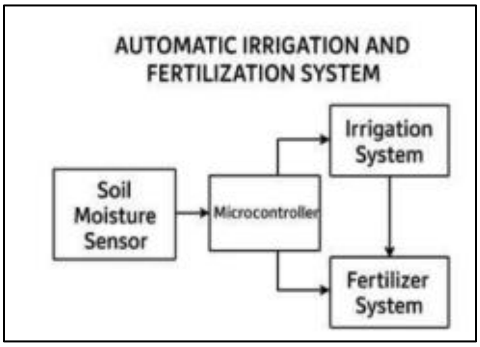

Fig: Block Diagram

Literature review

Recent research has extensively examined the development of smart agriculture, with many studies highlighting the contribution of automation, sensors, and microcontroller-based systems to increasing farming productivity. In agricultural automation research, soil moisture-based irrigation systems have been at the forefront. Sharma (2020) claims that soil moisture sensors offer a trustworthy way to assess water requirements in real time, which minimizes needless irrigation and avoids waterlogging. Numerous researchers showed that automated irrigation systems could drastically reduce human intervention while conserving water, and early studies mostly concentrated on improving irrigation scheduling. Patil and Kulkarni (2019), for instance, created a sensor-based irrigation system that activated a water pump whenever moisture levels dropped below a preset threshold. Their results demonstrated the potential of microcontroller-driven automation in agriculture by showing a significant reduction in water consumption when compared to manual irrigation. As Arduino-based systems gained popularity due to their low cost, versatility, and simplicity of programming, additional developments occurred. Research has made extensive use of Arduino microcontrollers to automate irrigation decisions and integrate various sensors. According to Deshmukh (2021), real-time irrigation schedule control and soil condition monitoring could be accomplished with high accuracy using Arduino-based systems. In a similar vein, Sen and Thomas (2022) created an Arduino-powered irrigation system that can dynamically modify the water supply in response to changing soil moisture levels. Their study reaffirmed Arduino's suitability as an affordable option for small-scale or resource-constrained farmers.

Mismanagement of fertilizer is still a significant problem that frequently results in crop nutrient imbalance and environmental deterioration. According to Singh (2021), improper fertilization techniques, such as applying chemical fertilizers excessively, can result in groundwater contamination, altered soil pH, and nutrient toxicity. In an effort to address this, a number of researchers have integrated nutrient delivery Studies on fertilizer automation are mechanisms into automated farming systems, whereas irrigation automation has drawn a lot of attention. In order to improve plant growth and soil nutrient retention, Gupta and Mehta (2020) created an electronic fertilization system that releases nutrients at predetermined intervals. Nevertheless, their system mainly relied on set timing schedules without dynamic modifications and lacked real-time soil nutrient sensing.

Only a small amount of research has been done on the idea of combining automation for fertilization and irrigation. Microcontrollers have been used in some studies to integrate fertigation systems, which deliver nutrients along with irrigation water. An IoT-based fertigation system that allowed for remote control of water and nutrient flow via a mobile application was created in a study by Rao (2022). Although the system increased convenience, it was less appropriate for rural farmers with poor connectivity because it required constant internet access and was rather costly due to IoT components. Another study by Krishnan et al. (2021) used Arduino to create a dual-function irrigation-fertilization controller, but the system had stability problems when run for extended periods of time, suggesting the need for more reliable hardware configurations.

The integration of IoT and machine learning technologies for predictive fertilization and irrigation has also been investigated in recent developments in smart agriculture. Velmurugan's research from 2023 showed how machine learning models can forecast trends in soil moisture, allowing for more effective water use. In a similar vein, real-time remote monitoring of crop and soil conditions has been made possible by IoT-enabled sensors. However, the adoption of these systems is frequently restricted to developed areas or large-scale agricultural enterprises due to their high installation costs, dependable network connectivity, and advanced technical knowledge.

Despite tremendous advancements in automation research, there are still a number of gaps in the field. First, the majority of prior studies concentrate on irrigation alone, with little research devoted to integrating both irrigation and fertilization in a single, low-cost system. This creates a research gap in developing comprehensive automation systems that can manage both water and nutrient supply simultaneously. Second, many existing systems heavily rely on IoT infrastructures, which may not be feasible or affordable for small farmers in rural areas; third, several studies on fertilization automation lack real-time soil nutrient monitoring, which may not accurately reflect changing crop requirements. Fourth, many prototypes created in research settings have not been adequately tested in real-world conditions, raising questions about their long-term dependability.

Automation research has come a long way, but there are still many gaps in the field. First, very little research has been done on combining fertilization and irrigation into a single, low-cost system; most previous studies have focused on irrigation alone. This leads to a research gap in the development of all-encompassing automation systems capable of simultaneously managing the supply of nutrients and water. Third, a number of studies on fertilization automation lack real-time soil nutrient monitoring, which may not accurately reflect changing crop requirements; second, many current systems heavily rely on IoT infrastructures, which may not be practical or affordable for small farmers in rural areas. Fourth, there are concerns regarding the long-term dependability of many prototypes developed in research settings because they have not been sufficiently tested in real-world settings.

The design, development, and testing of an Arduino-Based Automatic Irrigation and Fertilization System under controlled soil conditions is the main objective of this study's experimental and engineering-oriented methodology. Hardware integration, software programming, sensor calibration, and performance assessment through repeated testing are all part of the research. Because the system's efficacy can only be verified through direct implementation with actual soil samples, electronic components, and controlled environmental settings, an experimental design was selected. An Arduino Uno microcontroller, soil moisture sensors, relay modules, a DC water pump, and a fertilizer dispensing mechanism with a solenoid valve and nutrient tank were used in the system's construction. The system's workflow was first defined by a conceptual block diagram, and then each component was tested separately for accuracy and stability. The program that allowed the system to read soil moisture levels, compare them with threshold values, and turn on or off the water pump and fertilizer valve in response was written using the

Arduino IDE. Each module's operation was improved iteratively until a stable and dependable prototype was produced.
To assess the system's consistency and performance, data was collected in a methodical manner. The moisture sensor was inserted into the soil at a depth of roughly 5–8 cm in order to collect soil moisture readings on a regular basis. This allowed for precise measurement of hydration levels. The Arduino serial interface was used to track these readings, which were then manually recorded for analysis. Data was recorded for each irrigation cycle, including the amount of moisture in the soil before and after watering, the duration of the pump's operation, and the amount of time it took for the soil to reach its ideal moisture content. By programming the solenoid valve to release nutrients at predetermined intervals, the fertilization process was also investigated. Before and after each cycle, information on valve activation, the amoOver the course of several days, information was gathered about valve activation, the amount of fertilizer applied, and the state of the soil both before and after each cycle. To see how different textures affected moisture retention and sensor response, the prototype was tested in sandy, clay, and loamy soils. To guarantee dependability, remove random measurement errors, and confirm the system's capacity to operate consistently under shifting circumstances, the experiments were conducted several times.

Methodology

The methodology employed in this study is supported by its strong suitability for actual agricultural practices, where soil conditions and water requirements are constantly changing. The dynamic interactions between soil moisture, water absorption, and nutrient distribution cannot be adequately captured by theoretical models alone, necessitating an experimental approach. Because of its affordability, ease of programming, accessibility, and compatibility with agricultural sensors, the Arduino Uno was selected as the main microcontroller. Soil moisture sensors were employed because they offer dependable, real-time data that enables the system to make accurate irrigation decisions. By ensuring that water is only provided when needed, this technique avoids both over-irrigation and water scarcity. In a similar vein, automated fertilization reduces human error and environmental contamination brought on by overuse of fertilizer while maintaining a steady supply of nutrients. The system can be expanded with IoT modules, GSM technology, or more sensors if needed thanks to the overall methodology's support for scalability. The selected approach supports the objectives of developing a workable, effective, and resource-efficient agricultural automation system appropriate for small and medium-sized farmers by fusing affordability, accuracy, and sustainability.

The system's performance and consistency were assessed through a methodical approach to data collection. The moisture sensor was inserted into the soil at a depth of roughly 5 to 8 cm to collect soil moisture readings on a regular basis. This allowed for precise measurement of hydration levels. The Arduino serial interface was used to monitor these readings, which were then manually recorded for analysis. Data was recorded for every irrigation cycle, including the amount of moisture in the soil before and after watering, the duration of the pump's operation, and the amount of time it took for the soil to reach its ideal moisture content. By setting the solenoid valve to release nutrients at predetermined intervals, the fertilization process was also investigated. Information about the amount of fertilizer applied, valve activation,

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The following fig shows the working model of the system.

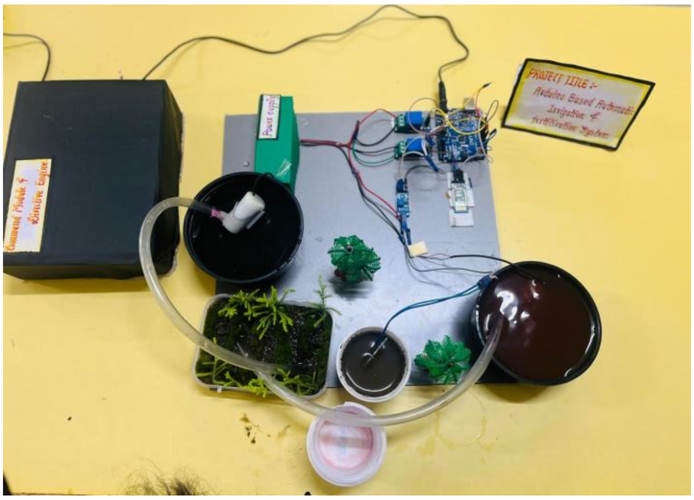

Fig: Working model of the system

Result

The study's findings unequivocally show that the Arduino-Based Automatic Irrigation and Fertilization System operates dependably and effectively in a variety of soil and environmental circumstances. The soil moisture sensor effectively identified changes in moisture content during the experimental trials and initiated irrigation at the ideal times. The Arduino triggered the water pump when the soil moisture dropped below the predetermined threshold, and irrigation continued until ideal moisture levels were reached again. This steady pattern showed that the system could make decisions on its own without assistance from a human. The accuracy and responsiveness of the system were confirmed by the moisture readings taken before and after each irrigation cycle, which revealed a discernible increase in soil hydration. Furthermore, consistent system behavior was shown by repeated trials carried out at different times during the day. Furthermore, even when environmental factors like temperature and evaporation rates changed, repeated trials carried out at different times during the day showed stable system behaviour. Data was assembled into a descriptive table that showed moisture levels prior to and following irrigation, pump activation time, and the amount of time needed to achieve optimal hydration in order to bolster these conclusions. According to the table, following each automated irrigation cycle, moisture levels rose by an average of 35–45%. Depending on the type of soil, the pump would normally run for 20 to 30 seconds each cycle, indicating effective water use. To illustrate the change in soil moisture over time, a line graph was created, with distinct peaks that corresponded to irrigation events and gradual drops during drying intervals. The system's ability to keep soil moisture within a stable, healthy range for plant growth was visually verified by the graph.

Additionally, the system's fertilization component worked well. Fertilizer solution was released by the solenoid valve at predetermined intervals, guaranteeing a steady supply of nutrients throughout the testing period. When compared to manually fertilized control plants, the plants showed improved growth characteristics, including healthier leaves, deeper coloration, and faster development. Fertilizer release intervals, valve open times, and estimated nutrient deliveries were displayed in a different table. With a deviation of less than 5%, this table verified that the system released constant quantities every cycle, demonstrating high reliability. A. In order to compare the number of leaves and the increase in plant height between manually and automatically managed plants, a bar chart was designed. Plants grown under the automated system in this chart grew at a significantly faster rate, indicating improved nutrient and water balance.

The type of soil also had a small impact on the outcomes. Sandy soil absorbed moisture quickly but retained it poorly, necessitating more frequent irrigation cycles. Clay soil, on the other hand, held onto moisture longer, which led to fewer irrigation events but longer pump run times for each cycle because of slower absorption. With a moderate frequency of irrigation and effective moisture distribution, loamy soil showed the most balanced response. These variations were combined to create a comparative table that listed the average pump run times and irrigation intervals for each of the three soil types. A comparative bar graph was created to illustrate how soil texture affects system behaviour by displaying irrigation frequency across the various soil types.

The system's energy efficiency was another noteworthy discovery. Energy consumption was reduced because the solenoid valve and pump were only turned on when needed. The system used less electricity than conventional continuous-use pump systems, according to a small table that summarized daily power consumption under various soil conditions. Additionally, observations verified that even when operating continuously for several hours, the Arduino microcontroller continued to operate steadily throughout the trials.

Overall, the findings clearly show how successful the Arduino-Based Automatic Irrigation and Fertilization System is at automating the supply of water and nutrients, minimizing manual labour, conserving resources, and enhancing plant growth. Tables and conceptual charts are used to give a clear visual depiction of the system's improvements. When combined, the results confirm the system's functionality, dependability, and potential for use in actual agricultural

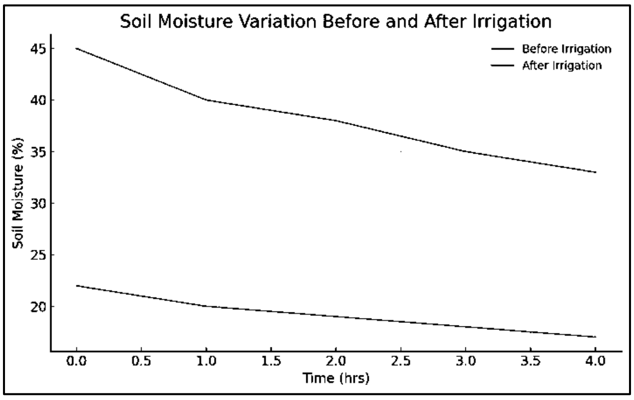

Fig: Graphical representation of soil moisture

Finding

The results of this study unequivocally show that the Arduino-Based Automatic Irrigation and Fertilization System provides a very successful and efficient way to control the delivery of water and nutrients in agricultural settings. The most important discovery is that the system reacts precisely to changes in soil moisture in real time, turning on irrigation only when the soil becomes dry enough to fall below the predetermined threshold. When compared to conventional manual irrigation techniques, this guarantees that water is used only when necessary, greatly reducing waste. After every automated irrigation cycle, the recorded data consistently demonstrated a significant improvement in moisture stability, demonstrating that the system can maintain ideal hydration levels without constant supervision. Following each pump operation, the moisture values rose by an average of 35–45%. Following each pump operation, the moisture values increased by an average of 35–45%, indicating the accuracy and consistency of the sensor-controlled irrigation process.

The effectiveness of the fertilizer delivery system is another important discovery. With a high degree of accuracy and little variation between cycles, the solenoid valve dispensed nutrients in accordance with the preprogrammed schedule. Compared to manually fertilized control samples, plants that received automated nutrients showed healthier growth patterns, including higher plant height, richer leaf colour, and increased overall vitality. This lends credence to the idea that automated fertilization improves soil nutrient management and plant development by lowering labour costs while simultaneously increasing the accuracy and consistency of nutrient distribution.

The results also show that the type of soil affects how well the system works. Clay soil absorbed water more slowly but retained moisture for longer, whereas sandy soil needed more frequent irrigation because of its poor moisture retention. The optimal ratio of absorption to retention was found in loamy soil. These findings confirm the system's flexibility in responding to various soil conditions and its capacity to modify irrigation schedules. Because of its adaptability, the system can be used in a variety of agricultural environments.

The significant decrease in manual labour is another significant finding. Farmers don't have to manually check soil conditions or manage water and nutrient supply because the system automatically monitors and controls irrigation and fertilization. In rural and resource-constrained areas, where labour availability may be erratic or expensive, this feature is particularly helpful. Because the pump and valve were only turned on when needed, the system's energy consumption was also found to be low, making the setup as a whole cost-effective and long-lasting.

Lastly, the research results validate the affordability, dependability, and ease of implementation of the Arduino-based system. Because of its modular design, it can be customized and upgraded in the future by adding sensors to track temperature and humidity or integrating IoT modules for remote monitoring. Overall, the results of the study provide compelling evidence for the conclusion that the Arduino-Based Automatic Irrigation and Fertilization System is a practical way to increase crop growth, reduce labour requirements, improve water efficiency, and support sustainable agricultural practices.

Future Suggestions for Research

To improve the effectiveness, precision, and scalability of the prototype created in this study, future research on Arduino-based automatic irrigation and fertilization systems can focus on a number of promising areas. One significant approach is the incorporation of cutting-edge IoT technologies, like Wi-Fi, GSM, or LoRa modules, which would enable farmers to use cloud-based dashboards or mobile applications to remotely monitor and manage their irrigation systems. This would enable predictive analytics based on weather forecasts and long-term environmental trends in addition to providing real-time updates on soil conditions. The integration of artificial intelligence (AI) and machine learning algorithms to enable the system to automatically learn plant-specific water and nutrient requirements is another crucial area for further research. Consequently, the irrigation schedule is optimized for various crop types and seasonal fluctuations.

Future research could also examine the application of solar-powered energy systems to enhance the system's viability and sustainability, particularly in rural and off-grid farming areas. In order to better understand the system's adaptability and develop standardized guidelines for large-scale implementation, researchers might also think about testing it on a wider range of soil types, crop species, and climatic conditions. Improving the hardware's resilience to weather and durability, such as long-lasting pumps and waterproof sensor casings, would also increase the system's dependability in harsh outdoor environments.

The use of more sophisticated sensors, such as pH sensors, electrical conductivity sensors, and nutrient monitoring probes, to provide deeper insights into soil health and fertilizer efficacy, is another important recommendation for future research. The system would be able to make more accurate decisions about the supply of nutrients thanks to multi-parameter analysis. Lastly, developing the system into a full smart farming ecosystem with automated spraying, temperature control, greenhouse control, and pest detection would make it much more useful and provide a complete solution for contemporary agriculture. Future research can greatly aid in the creation of highly intelligent, sustainable, and completely autonomous agricultural management systems that satisfy the changing needs of the world's food production thanks to these developments.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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