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Design of Smart Plant Electrical Signal Monitoring System for Indoor Farming

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Abstract. Precision agriculture is widely applied in indoor farming to optimize resource use and improve sustainability. Spectral technology has limitations in operation in plant health monitoring in indoor farming. A concept of plant physiology, plant electrical signals, is able to be developed as a basic principle in plant health monitoring systems. This research investigates the design of a plant monitoring system based on plant electrical signals. The system integrates Ag wire electrodes for acquiring plant electrical signals. Low-pass filters and operational amplifiers are utilized signal processing, while microcontrollers and data loggers handle data storage and analysis. Calibration for this system needs a function generator. The calibration result is analyzed using statistical methods such as MAPE. The system will apply various advanced analysis techniques such as time domain, frequency domain, and machine learning methods. The goal of such analysis is to improve early detection of plant stress contributing to more efficient crop management in indoor farming systems. This monitoring system potentially improves plant health and supports sustainable agricultural practices. By leveraging the rapid response of plant electrical signals to environmental changes, the system is the first step for optimizing plant growth by providing real-time monitoring and environmental recommendations.

1. Introduction

Precision agriculture is currently being widely applied in replacing conventional agriculture. Implementation of precision agriculture is performed through applying the right amount, right time, and right location of inputs [1]. In this application, precision agriculture requires the integration of the Internet of Things, Artificial Intelligence, and Big Data [2,3]. The benefits of implementing precision agriculture include maximizing crop yield with optimizing inputs and maximizing environmental sustainability [4].

The application of precision agriculture can be carried out in indoor farming [5]. In indoor farming, precision agriculture contributes to control of micro-climatic conditions, nutrient feeding, and automation/robotics [6, 7, 8]. The application can be actualized through sensor technology which can be environmental sensors, spectral sensors, gas sensors, and chemical sensors.

Imaging technology, which is realization of spectral sensor, is a powerful tool for plant health identification and plant phenotyping. These technologies include fluorescence imaging, hyperspectral imaging, thermal imaging, and multispectral imaging [9]. Some limitations of these technologies are complicated analysis, highly-skill operation, high cost, sensitive to ambient light condition, and huge dataset. In addition, imaging technologies are only capable to get the extensive traits of plant [10].

Plant electrical signal is a type of the signaling method in plants. This trait is categorized as one of the intrinsic plant phenotyping. Plant electrical signal has rapid response on environmental changes [11, 12]. Those responses relate to physiological properties of plant relating to the final yield. By utilizing plant electrical signal, there is a chance to develop a plant health monitoring system which is more precise and responsive in detecting early signs of plant stresses and diseases. Therefore, the aim of the study is to present the design of plant monitoring based on plant electrical signal. This system offers for optimizing the input and maximizing of sustainability in indoor farming.

2. Literature Review

Research on plant responses primarily plant electrical signals has been conducted since the late 18th century. Some of the researchers at that time included Charles Darwin, John Burdon-Sanderson, and Jagadish Chandra Bose [13, 14, 15, 16, 17, 18]. Darwin expressed his idea that the root end of the plant acts like a brain that processes the stimuli received by the plant and then directs the movement of the plant. This research shows

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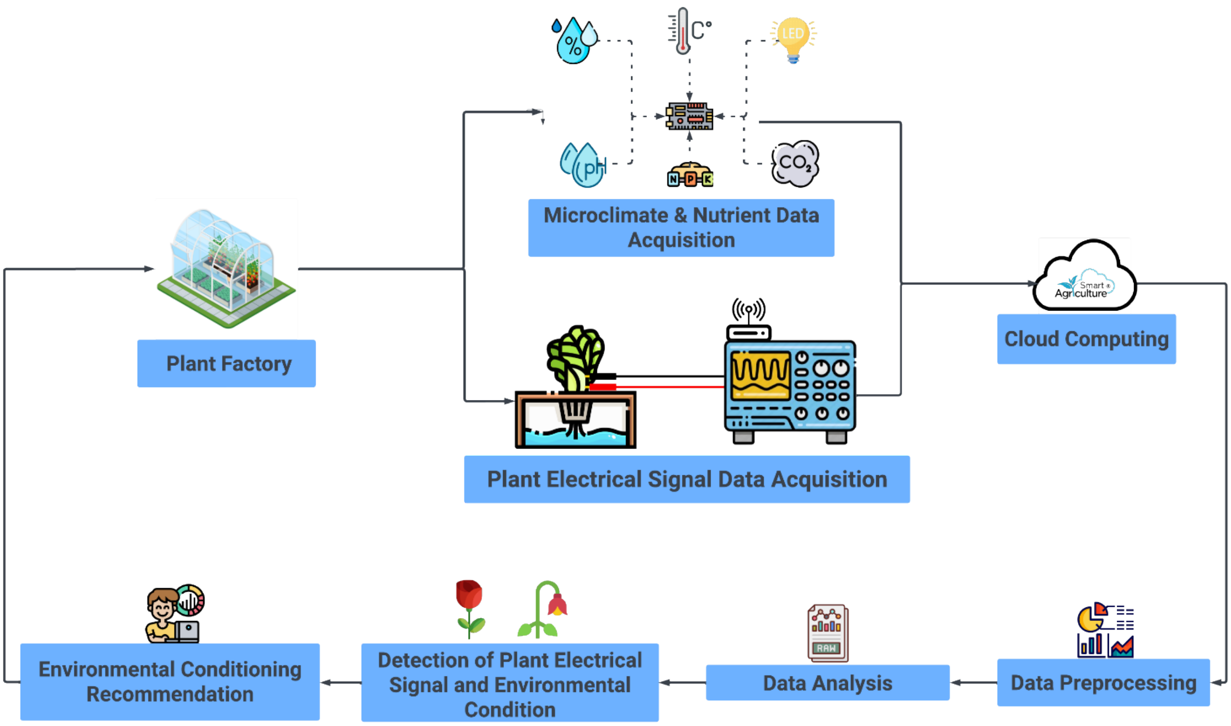

Fig. 1. Conceptual Framework of Plant Electrical Signal Monitoring System

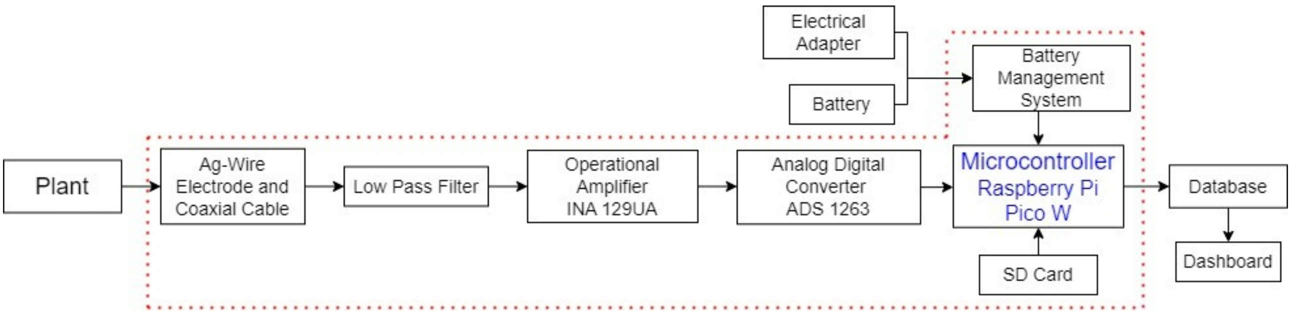

Fig. 2. Block Diagram of Plant Electrical Signal Monitoring System

that plants can respond to external stimuli. John Burdon-Sanderson studied plant response through changes in electrical voltage in the leaves of *Dionaea muscipula*. The study was continued on the *Mimosa pudica* by Jagadish Chandra Bose. The study was the beginning of the concept of action potential and variable potential. Plant electrical signals are a plant physiological response in the form of electricity to external stimuli [19]. The existence of electrical signals is a manifestation of action potential, variation potential. The two forms of electrical signals have different roles. The potential for action arises due to triggered by changes in environmental condition. Variation potential is formed due to physical damage on plant.

Plant electrical signals are formed in the plasma membrane of plant cells. The formation is based on ion channel activity. Some ions related to the formation of plant electrical signals are Ca^{2+}, Cl^-, K^+, and H^+-ATPase [20]. The formation of electrical signals occurs due to Ca^{2+} ions entering the cell. This phenomenon causes depolarization (the cell is in a positive condition). The process is followed by activation of the chloride ion channel (Cl^-) so that Cl^- ions leave the cell. Cell repolarization, a change in cell state back to negative, occurs when the potassium (K^+) ion channel opens so that K+ ions leave the cell. The difference between the formation of action potential and variation potential is in the activity of H+-ATPase [13]. Variation potential triggered by damage stress causes deactivation of H+-ATPase at the plasma membrane so that depolarization lasts long. Deactivation of H+-ATPase causes a decrease in ion pump activity.

Plant electrical signals are closely related to the physiological characteristics of plants. Changes in plant electrical signals can affect the process of photosynthesis, phloem transport, respiration process, and plant growth [14]. Therefore, monitoring plant electrical signals is important. The monitoring is carried out to maintain plant electrical signals so that plant growth and development can be optimized.

3. Methodology

a. Conceptual Framework

This study discusses a plant electrical signal monitoring system for indoor farming systems.

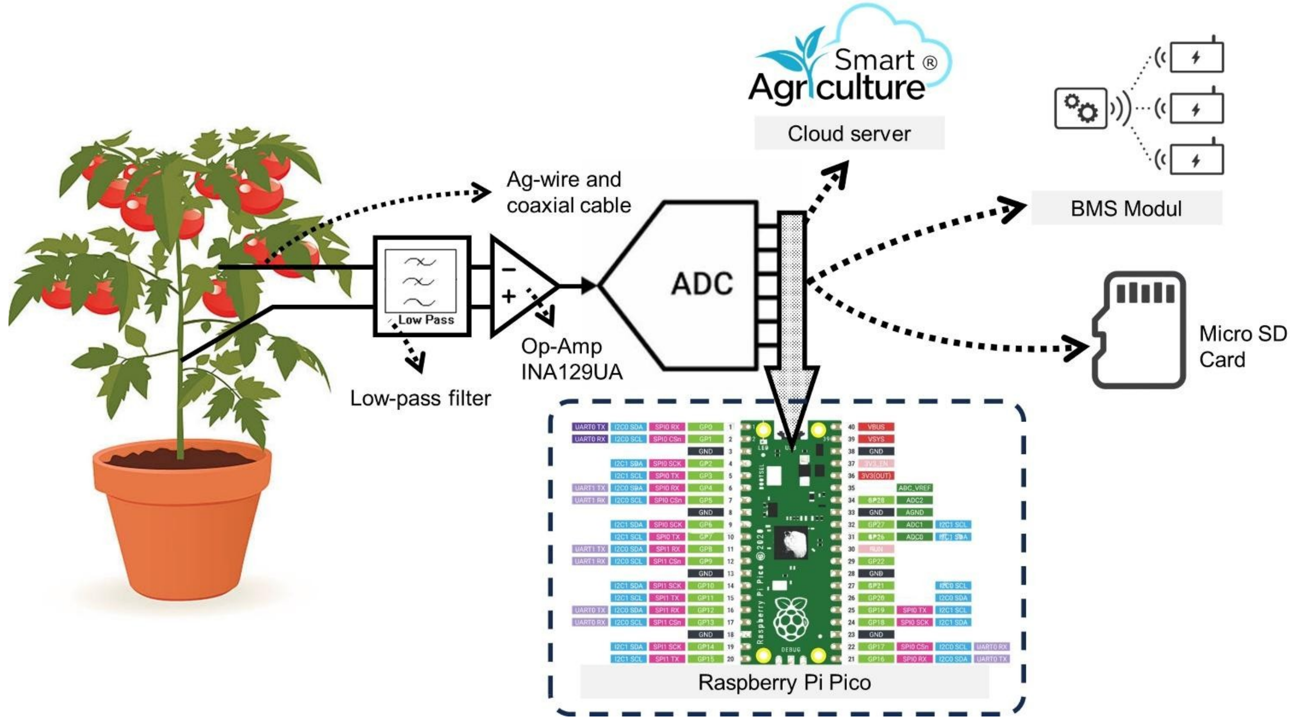

Fig. 3. Design of Plant Electrical Signal Monitoring System

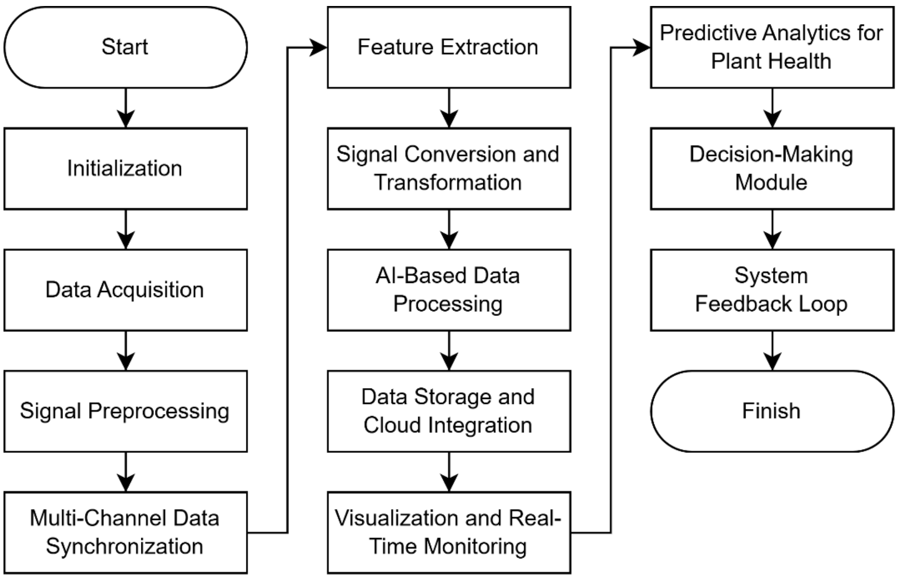

Fig. 4. Algorithm Diagram of Plant Electrical Signal Monitoring System

The framework of this study is shown in Figure 1. The framework is comprised of four steps. The framework starts with the simultaneous acquisition of plant electrical signal data and environmental data (1). The environmental data consisted of air temperature and temperature, air humidity, light intensity, carbon dioxide gas concentration, nutrient water content, and nutrient water pH value. The data collection is done online in a cloud (2). Data preprocessing is performed on the data (3). Data preprocessing consists of noise reduction, normalization, segmentation, and feature extraction. The analysis stage is carried out on the data resulting from the data preprocessing stage (4). Thedata analysis stage includes time domain analysis, frequency domain analysis, non-linear analysis, and modeling using machine learning. The final result of modeling is the ability of the system to detect environmental stress in plants based on plant characteristics.

b. Design of Monitoring System

In this study, a plant electrical signal monitoring system is proposed. The plant electrical signal monitoring system is comprised of four electronic modules, a low pass filter, an operational amplifier, and a customized sensor. The customized sensor is composed of a silver wire and a coaxial cable (RG178/U, Pasternack Enterprises Inc, Switzerland). A simple low pass filter is composed of a potentiometer and a one micro farad capacitor. The operational amplifier is an IC INA 129UA. Some of the modules used in this system consist of a microcontroller (Raspberry Pi Pico W, Raspberry Pi Foundation, United Kingdom), electrical signal converter (ADS 1263, Texas Instruments, United State America), data logger (MicroSD card breakout board+, Adafruit, United State America)

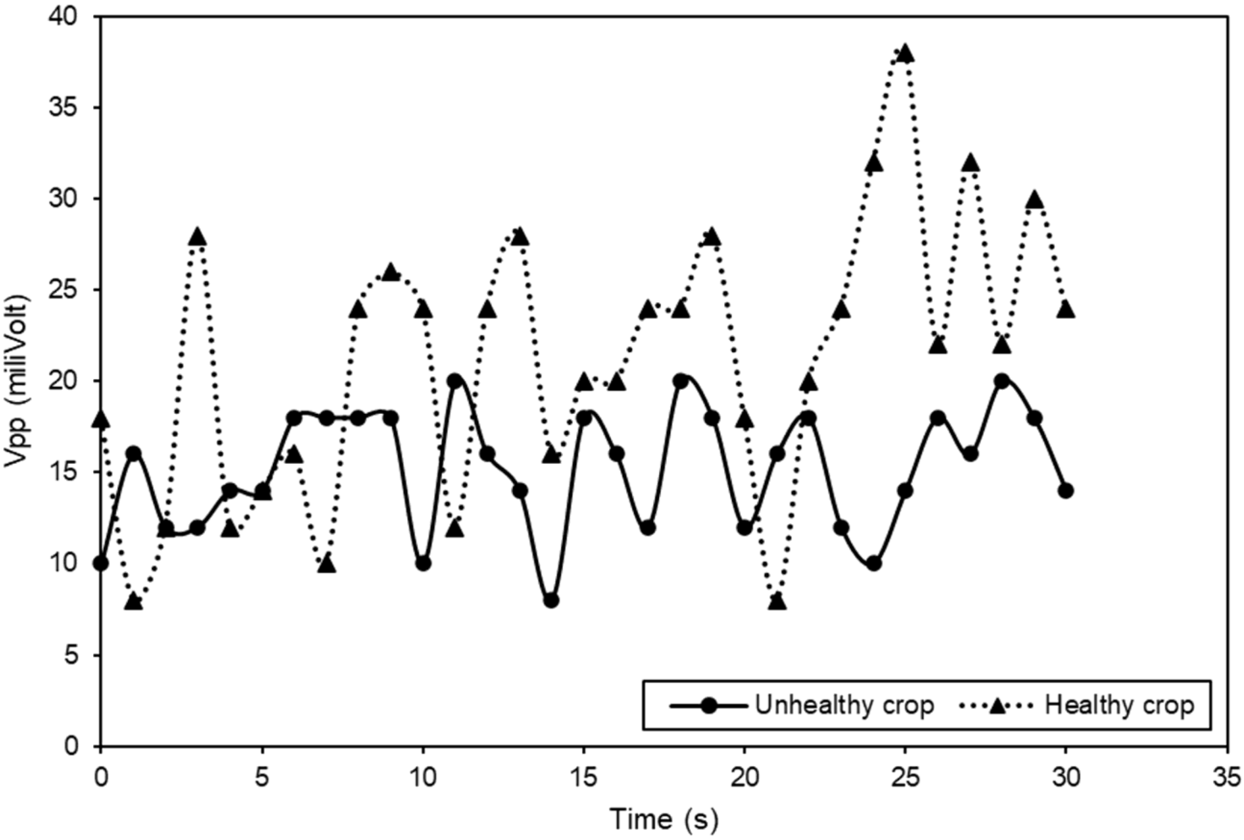

Fig. 5. Representation of Plant Electrical Signal Data

and battery management system (UPS HAT, Wave share, China). A block diagram of the plant electrical signal monitoring system is shown in Fig. 2. Figure 3 illustrates the design of the plant electrical signal monitoring system. The plant electrical signal monitoring system is intended for monitoring indoor farming systems. The Electrical signal acquisition process will be conducted at a sample rate of 500 Hz. The acquisition of plant electrical signals is carried out through a sensor composed of Ag wire and coaxial cable. Ag wire is used as a medium for acquiring electrical signals in plant organs. The coaxial cable serves to connect the Ag wire with the next set of components and retain electromagnetic wave noise from the environment.

The acquired plant electrical signal data is processed in the low pass filter module and operational amplifier module. The low pass filter is needed to eliminate electromagnetic waves recorded on the Ag wire. The low pass filter is designed for cut-off frequencies at 1, 5, 10, 15, 20, and 25 Hz. These values need to be studied further so that plant electrical signals that are affected by environmental conditions can be reached and identified by this system. The resulting data was amplified at gain values of 10, 100, 1000, and 10000. The selection of the gain value requires further study so that the acquired electrical signals can be read by the signal converter module.

The amplified electrical signal data is converted into digital signals using a signal converter module. In addition, the signal converter module sends the plant electrical signal data to the microcontroller module. The plant electrical signal data is sent to the database in the form of a cloud and stored in the storage memory by the microcontroller. The data will be further processed on the dashboard.

Figure 4 shows the algorithm diagram of the plant electrical signal monitoring system. The algorithm is aimed at evaluating plant health in indoor farming based on plant electrical signals. The system starts with initialization in the form of sensor calibration and connectivity checking. The system captures plant electrical signals continuously along with recording environmental data such as light intensity, air temperature and humidity, carbon dioxide concentration in the air, and concentration of a compound in the nutrient water. The electrical signals are preprocessed including noise reduction, artifact removal, feature extraction, multichannel data synchronization, and signal conversion into digital data. Machine learning models are applied to predict plant health followed by storage of results and data to the cloud. The system also includes predictive analytics to assess future plant health and provide actionable insights to optimize farming practices. Records in the form of automated reports are generated followed by continuous feedback to fine-tune the accuracy and efficiency of the system. It enables responsive and optimized monitoring solutions.

4. Discussion

The purpose of this research is to present an initial concept and design for a plant electrical signal monitoring system, with a focus on indoor farming. A specific application of the indoor farming technology is a plant factory with artificial microclimate control. Monitoring plant health is crucial because numerous environmental conditions influence plant growth, development, and eventual yield.

The monitoring system utilized in this study is based on the concept of plant electrical signals. This system consists of easily reachable components. To guarantee the measured signal values are accurate, the system must be calibrated. Calibration can be done using different electrical signal measurement methods, such as function generators and oscilloscopes. The results of reading plant electrical signal levels between the proposed and comparator systems will be examined statistically using MAPE. The reading of plant electrical signals using this technology is supposed to provide a curve line plotting electrical signal voltage against time (as illustrated in Figure 5).

The plant electrical signal monitoring system in this study is only aimed at indoor farming systems. The selection of the indoor farming system is based on the controllable environmental conditioning. The application of the plant electrical signal monitoring system is possible in open field farming systems by considering the robustness of the battery and system due to the effects of sunlight heat. In addition, the selection of an appropriate communication method needs to be studied further so that the system can work in real-time.

The plant electrical signal monitoring system is designed to identify stress conditions found in plants. Heat stress, cold stress, dry stress, flood stress, and lightless stress are all potential stresses in an indoor farming system. Plants under normal conditions (according to the desired requirements) have a consistent electrical signal pattern per unit of time [21]. Chi-Chia stated that plants under stress will have an increase in the peak-to-peak value of the electrical signal [22]. This may affect the electrical signal pattern of the plant. Temperature stress leads to increased electrical signaling. Furthermore, a rise in atmospheric humidity increases the plant's electrical signal. Light reduces the plant's electrical signal. Plant electrical signals also decrease when exposed to ozone pollution.

Recognizing plant electrical signal patterns under specific conditions is required to maximize plant growth and development. Plants can be stressed by a variety of factors, including microclimate, nutrition, water, pest, and disease. Numerous earlier investigations on plants under nutritional stress have been carried out [23, 24, 25]. The findings of these investigations typically lead to the identification of electrical signal patterns in plants under diverse stress situations (dry, nutritional, and insect). The study did not specify the level of stress the plants experienced in terms of electrical impulses. This is critical in agricultural management to determine the possibility for plants to return to normal circumstances and the impact on harvest output.

Previous investigations on plant electrical signaling were often undertaken on model plants (*Arabidopsis thaliana*). However, research into plant electrical signaling in cultivated plants has been limited. In relation to this study, the proposed monitoring system would investigate hydroponic plants. Some of the hydroponic plants to be used are Chinese Kale (*Brassica oleracea*), Lettuce (*Lactuca sativa*), and Water Spinach (*Ipomoea aquatica*). The proposed monitoring system must be modified to work on larger plants like mangoes and bananas. This is done to enable sensor penetration and ensure system robustness.

Plant electrical signals are associated with plant physiology and productivity. A stressor causes alterations in electrical signaling and plant physiology. According to Grienberg, beta ray radiation on plants reduces their ability to assimilate carbon dioxide and photosystems [26]. According to Mudrilove, heat stress has an effect on photosystem capacity, NPQ, and hormone levels [27]. The presence of stress can affect the balance of the plant's biological system. This has an impact on disrupting plant growth and development.

To avoid disrupting plant growth and development processes, this study's monitoring system focuses on creating a stress detection system. Other advancements can be made to anticipate nutritional requirements based on a nutrient's stress levels. It is necessary to create a database of plant electrical signal patterns caused by diverse stressors. The database can be used to build plant growing strategies using the most optimal scenario. Furthermore, this research's next work will focus on developing predictive analytic approaches between an electrical signal pattern and its harvesting yield.

5. Conclusion

This study describes the development of a plant electrical signal monitoring system for indoor agriculture. The system monitors plant health and stress levels in real-time. The system consists of Ag wire electrodes, low-pass filters, operational amplifiers, and microcontrollers that enable for precise acquisition, processing, and storage of plant electrical signal data. The system is cloud-integrated, allowing for real-time monitoring and quick decisions. The system is expected to recognize plant stress indicators and make recommendations for optimizing plant growth based on additional data analysis methods such as time domain, frequency domain, and machine learning. This monitoring system has the potential to improve resource management and productivity in indoor farming. The future work of this research needs to establish a predictive analysis strategy for approaching the relationship between an electrical signal pattern and harvesting yield.

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