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A real-time optical monitoring technology for sustainable hydroponic crop management

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ABSTRACT

Indoor vertical farming is crucial for solving future food challenges, especially in arable land-scarce countries. Among various techniques, hydroponics, which relies on nutrient-enriched water rather than soil to grow crops, has gained significant traction. However, optimizing crop yield while minimizing manual labor remains a challenge, particularly in automating crop health monitoring and nutrient replenishment. Currently, these processes are labor-intensive, prone to human error, and often subjective. While previous studies have utilized imaging techniques for detecting plant stress, monitoring chlorophyll content, and other health indicators, a fully integrated and automated system is still lacking. Current nutrient monitoring relies on tools such as electrical conductivity and pH meters, which provide only limited feedback on nutrient imbalances, inadequate to identify specific deficiencies or elemental concentrations accurately. To address these gaps, we propose a comprehensive monitoring system that combines two advanced modalities: imaging spectroscopy and laser-based elemental spectroscopy. This system includes imaging spectroscopes for monitoring crop health and a real-time nutrient analysis system based on laser-induced elemental spectroscopy for in situ quantitative chemical composition analysis of the nutrient solution. This comprehensive system will automate health monitoring and nutrient management, improving crop productivity and significantly reducing manual labor. The current prototype is optimized to swiftly identify crop growth stages, detect nutrient deficiencies, and quantify specific nutrient levels in green lettuce species. This advancement represents a significant step toward enhancing the efficiency and sustainability of indoor vertical farming.

Keywords: hyperspectral imaging, laser-induced breakdown spectroscopy, crop monitoring, SVM, nutrient monitoring, smart agriculture

1. INTRODUCTION

Indoor vertical farming is emerging as a pivotal solution to global food security challenges, particularly in regions with scarce arable land [1]. Among the diverse methodologies employed in indoor agriculture, hydroponics stands out for its efficient utilization of water-based mineral solutions to nurture crops [2]. Essential inputs for a hydroponic system include automated control of ambient temperature, light exposure, water, nutrients, and oxygen delivery to the crops [3]. Although nutrient formulations are tailored to meet crop-specific needs, their levels gradually decrease or deviate from optimal values due to transpiration, with the rate of change depending on the crop type and growth stage [3]. Therefore, continuous monitoring of crop health and nutrient levels is critical for maintaining high-quality yields throughout the year [3, 4].

Currently, many hydroponic farming tasks depend on manual efforts and subjective evaluations, which limit optimization and automation potential [5]. Although previous research has delved into imaging techniques for identifying plant stress [6] and monitoring chlorophyll levels [7, 8], there lacks a comprehensive system capable of managing all aspects of hydroponic crop health. Moreover, traditional nutrient analysis methods, such as electroconductivity and pH measurements, offer only a basic understanding of nutrient dynamics within the system [9]. These techniques lack the precision needed to identify specific nutrient deficiencies or toxicities accurately. This highlights a critical gap in effectively monitoring and adjusting nutrient levels. To maximize crop yield and reduce manual labor, there is an urgent need to develop a real-time, automated system for crop health monitoring and nutrient management.

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In this context, this research proposes an integrated approach: a comprehensive monitoring system that combines imaging spectroscopy with laser-based elemental spectroscopy. By integrating these advanced photonic technologies, the system aims to transform the management of indoor hydroponic farms. It enables quick identification of crop growth stages, early detection of stress in lettuce crops, and accurate measurement of specific nutrient levels in the nutrient solution. The research focuses on the design, implementation, and evaluation of this system, highlighting its potential to revolutionize indoor farming practices. The proposed system is expected to significantly enhance the efficiency, productivity, and sustainability of indoor vertical farming.

2. METHODOLOGY

The developed monitoring system, as shown in Figure 1, consists of two primary components: crop health monitoring (Part A) and nutrient supply monitoring (Part B). Part A focuses on monitoring crop health using a hyperspectral imaging (HSI) system. Hyperspectral imaging technology captures detailed spectral data across a broad range of wavelengths, offering accurate insights into the physiological and biochemical characteristics of materials, making it a versatile tool for analysis and monitoring across various applications [10-14]. The system used in this research includes a hyperspectral imaging camera (Resonon, Pika XC2, 400 nm–1000 nm) equipped with an imaging lens (Schneider, Xenoplan 2.8/50-0902), offering a spectral resolution of 1.3 nm. The imager, designed in a push-broom configuration, is mounted on a synchronized rotational stage (Arcus Technology, DMX-J-SA-17) for precise imaging. A broadband light source is used as the illumination source to illuminate the sample under investigation. Captured hyperspectral images are processed using a Support Vector Machine (SVM) classifier, a robust supervised machine learning algorithm widely used in agricultural research. SVM trains on labeled data and separates different classes by creating a hyperplane as a decision boundary [15]. SVM also offers a significant advantage as it can handle both classification and regression problems [16].

Part B involves monitoring the nutrient supply using a laser-induced breakdown spectroscopy (LIBS) system. Laser-Induced Breakdown Spectroscopy (LIBS) technology allows for rapid, non-destructive elemental analysis by detecting the unique spectral signatures emitted from a material [17-21]. Laser pulses (1064 nm, 6 ns duration) from an Nd: YAG laser (Quantel, Q-smart 850) were directly focused onto a quartz cell containing the nutrient solution using a bi-convex lens with a focal length of 50 mm. The emission from the plasma was collected using another lens and transported to the entrance slit of a Czerny-Turner (Kymera 328i, Andor) spectrometer. Throughout the experiment, the parameters were maintained as follows: laser energy at 15 mJ, gate delay at 300 ns, and gate width at 1000 ns. The analysis of the resulting atomic and ionic emission spectra captured from the plasma enables real-time identification and quantification of elemental components.

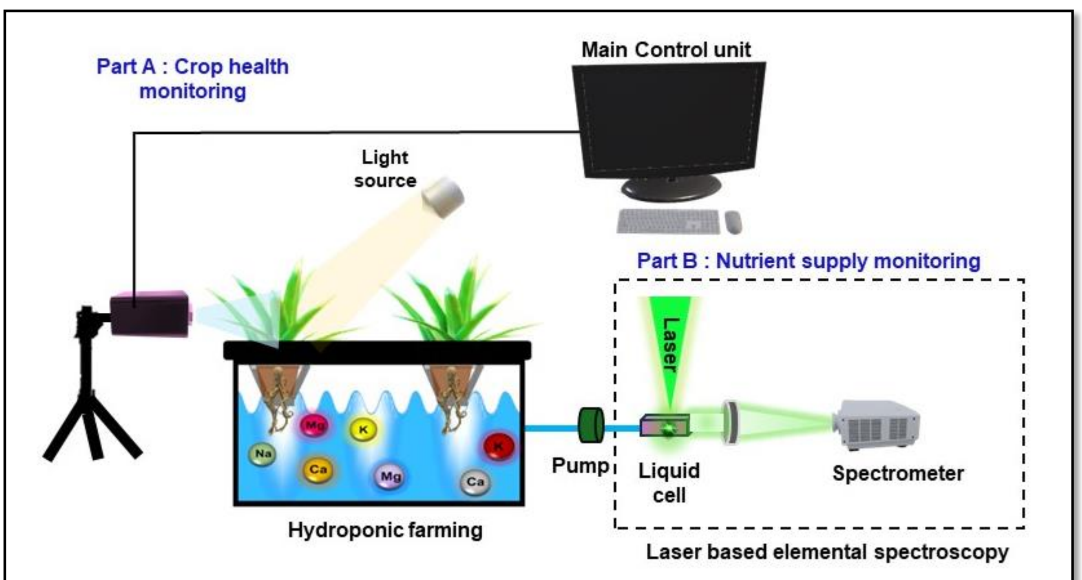

Figure 1. Schematic diagram of the developed system.

Parts A and B are integrated into a centralized control unit, enabling synchronized operation for improved accuracy and efficiency. This integrated system enhances the monitoring and management of indoor vertical farming practices, offering a non-invasive, real-time approach for assessing crop health and nutrient supply.

Lactuca sativa L. crops (commonly known as green lettuce) were cultivated in two separate trays. One tray, referred to as the reference tray, was supplied with an optimal nutrient composition. The second tray was provided with a nutrient mixture that was deficient in several key elements (including 78% less calcium, 65% less potassium, and 95% less iron). The variations in crop growth between the two trays were analyzed using a spectral library developed for this purpose.

3. RESULTS AND DISCUSSION

Crop health monitoring: Images of *Lactuca sativa L.* crops grown in tray 1 (reference tray) and tray 2 (deficient tray) were acquired using the VIS-NIR spectral camera on different days along the crop life cycle (referred to as days after planting (DAP)). A reference library was created using data cubes captured from healthy and stressed crop samples of reference and deficient tray from DAP 35 and the spectrum based spatial features were extracted. Features extracted were labelled as stressed crops, healthy crops, regions with low (labelled as dull and dark regions), and high reflectance. SVM classification was performed based on this created library, and the image for DAP 21 is shown in Figure 2 (A) and (B).

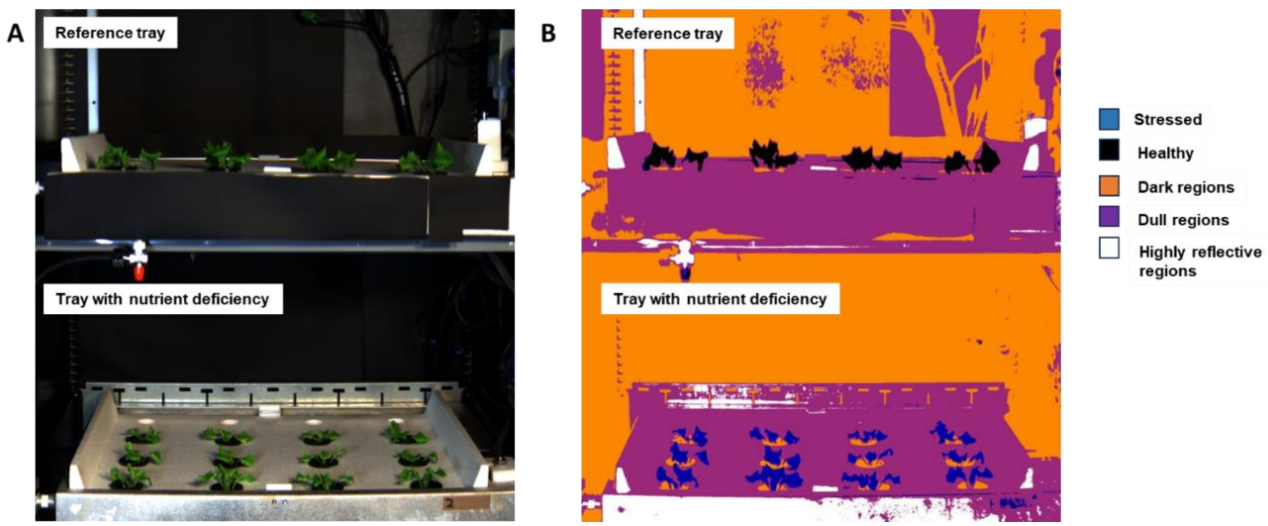

Figure. 2. (A) Representative RGB image derived from HSI data and (B) SVM classification of the image showing stressed and healthy crops at DAP 21. Color maps for stressed and healthy regions of crops were indicated by blue and black colors respectively.

The developed SVM model successfully categorized the features in the input HSI cube. The model demonstrated its ability to identify and correctly classify crops as either healthy or stressed. Additionally, SVM model training was conducted to detect crop stress at the early stages of nutrient deficiency. For this purpose, three classes were defined: healthy, stressed, and dark. Ground truth data was labelled using the Spectral Angle Mapper (SAM) method. The healthy class corresponds to regions with healthy crops, the stressed class includes areas with stressed crops, and the dark class represents non-crop or dark regions. Representative results for model prediction for healthy and stressed crops are shown in Figure 3.

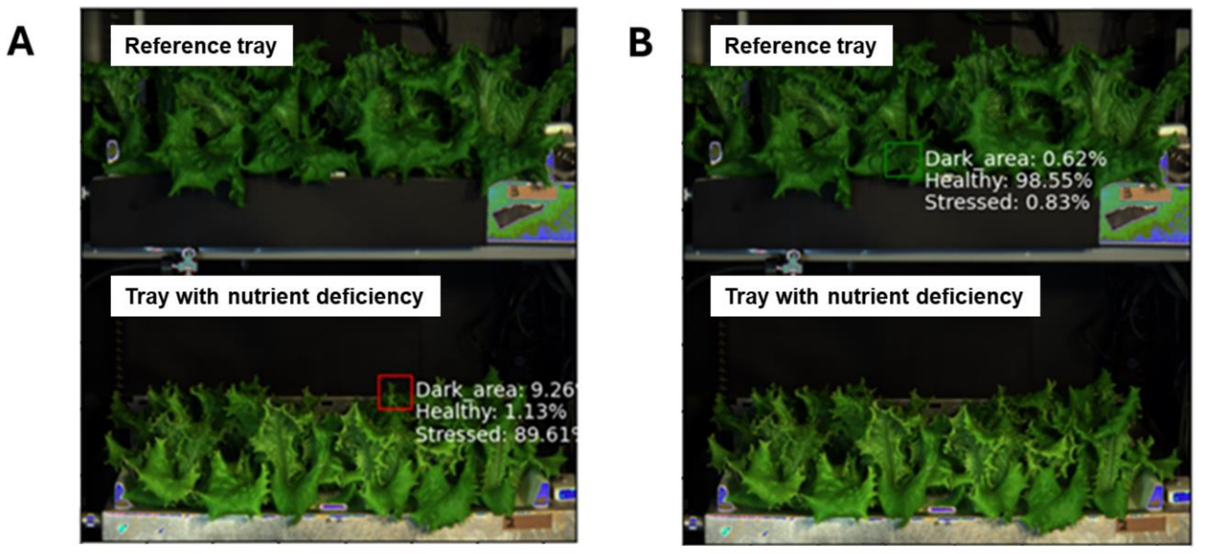

Figure. 3. SVM model prediction outcomes for (A) stressed and (B) healthy crop.

Three types of kernels were studied for building SVM models: Radial Basis Function (RBF), Linear, and Linear Probability. The results showed that while the RBF SVM model takes more time to make predictions, it provides higher accuracy for the same dataset compared to the Linear SVM models. The Linear Probability SVM model, on the other hand, is quicker in predictions than the standard Linear SVM model. Overall, all the models achieved an accuracy of over 95% in predicting crop health across all growth stages.

Nutrient monitoring: The recorded LIBS spectra for two types of nutrient solutions are shown in Figure 4 (A) and (B). The potassium (K I) emission lines at 766.5 nm and 769.9 nm exhibited a marked decrease in intensity in the deficient solution, indicating a lower potassium concentration. Similarly, calcium (Ca I) emissions at 422.6 nm showed reduced intensity in the deficient solution, reflecting a diminished calcium concentration. For each measurement, the signal-to-background (S/B) ratio was determined by dividing the peak intensity by the average background value. The S/B ratio for potassium and calcium in the normal and deficient solutions were found to be 3.1 and 1.3, and 6.2 and 2.6, respectively. The reduction confirms the lower concentration of potassium and calcium, validating the ability of LIBS to detect nutrient deficiencies.

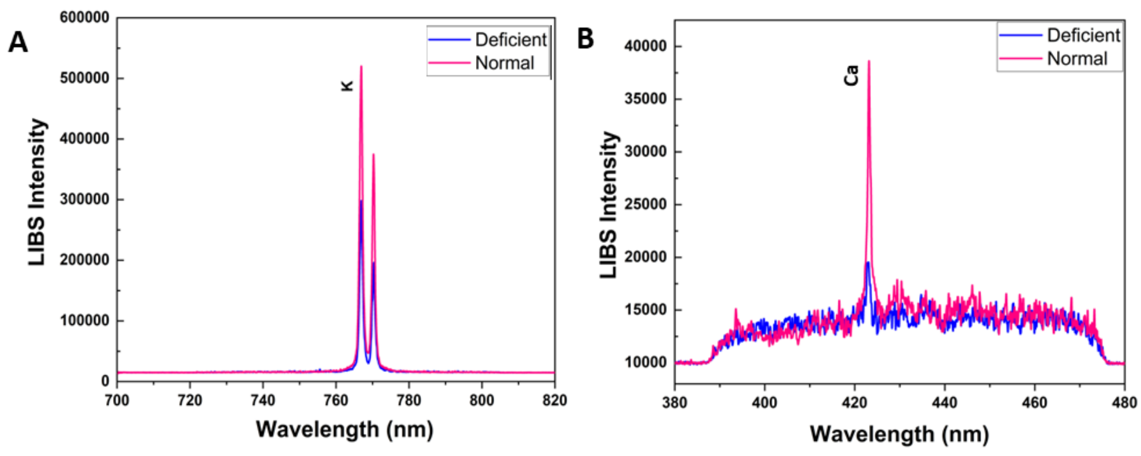

Figure. 4. LIBS spectra of nutrient solution for deficient and normal samples showing (A) potassium (K) and (B) calcium (Ca) emission lines.

The results demonstrate the effectiveness of an integrated LIBS and HSI system for monitoring crop health and identifying nutrient deficiencies. This approach offers accurate and precise detection of crop stresses, contributing to improved crop yields and minimizing losses. Such systems could hold significant potential for advancing future sustainable agriculture practices.

4. CONCLUSION

In conclusion, the integration of SVM based HSI and LIBS presents a transformative advancement in indoor vertical farming. This comprehensive monitoring system addresses critical challenges such as optimizing crop yield and managing nutrient levels in real-time. By leveraging LIBS for rapid nutrient analysis and HSI for crop health monitoring, the system enhances the precision of crop health assessment by detecting stress indicators in lettuce species. This technology holds immense potential to enhance sustainability and efficiency in agriculture, paving the way for resilient food production systems capable of meeting global food security demands in a resource-constrained world.

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