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LIBS: A rapid nutrition monitoring tool for hydroponic crops and nutrient supply

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ABSTRACT

Hydroponic systems offer controlled environments for crop growth, demanding precise and continuous monitoring of nutrient levels to optimize plant health and yield. In-situ monitoring of crops and nutrient supply plays a pivotal role in comprehensively understanding their mineral constituents, facilitating early correction of nutritional deficiencies. In addition to detecting nutritional deficiencies, this process offers farmers guidance regarding precise crop cultivation practices. However, current monitoring techniques are often labor-intensive, laboratory-based, and require tedious sample preparation. In this context, we propose an optically modified direct spectrograph-coupled laser induced breakdown spectroscopy (LIBS) system capable of detecting and quantifying key nutrients including potassium, calcium, and magnesium. In this work, in-situ nutrient monitoring of the nutrient supply and lettuce crop was performed using single-shot LIBS. Analysis of the results elucidates that highly sensitive and reproducible LIBS spectra can be directly obtained without any sample preparation. Additionally, we assess the feasibility and accuracy of LIBS in capturing dynamic changes in nutrient concentrations, providing valuable insights into nutrient uptake kinetics and potential imbalances. This research showcases LIBS as a valuable tool for real-time monitoring in hydroponic systems, highlighting its potential for remote analysis in agriculture. It facilitates informed decision-making and enhances the overall efficiency of nutrient management practices in agricultural fields.

Keywords: Hydroponic systems, nutrient monitoring, laser-induced breakdown spectroscopy, nutrient deficiencies, real-time monitoring

INTRODUCTION

In recent years, hydroponic farming has emerged as a sustainable and efficient method for cultivating crops, offering significant advantages over traditional soil-based agriculture [1]. This soilless growing technique enables precise control over nutrient delivery, optimizing plant growth and resource use efficiency. However, maintaining the ideal nutrient balance is critical, as any deviation can adversely affect plant health and productivity. One of the key challenges in hydroponic systems is managing salinity levels in the nutrient solution, as high salinity can lead to osmotic stress, ionic toxicity, and nutrient imbalances, ultimately impacting crop yield and quality [2]. Salinity management is particularly crucial in hydroponic systems where the water and nutrient solutions are recycled, potentially leading to salt accumulation over time. Monitoring the effects of salinity on plants can provide valuable insights into their physiological responses and help in developing strategies to mitigate adverse impacts. Traditionally, assessing the nutrient status and salinity effects on plants involves destructive sampling and labor-intensive chemical analysis methods, which can be time-consuming and impractical for automated real-time monitoring.

There is a critical need for advanced in-situ monitoring technologies capable of providing precise, continuous, and non-invasive nutrient analysis to address these limitations. In this context, we introduce an optically modified direct spectrograph-coupled LIBS system designed specifically for hydroponic applications [3,4]. LIBS enables the real-time detection of elemental compositions [5], offering a quick and efficient way to monitor the nutrient status and salinity levels in hydroponic plants and nutrient solutions. This technique involves focusing a high-energy laser pulse on the plant tissue or nutrient solution, creating a plasma that emits light characteristic of the elements present [6]. By analyzing the emitted spectra, it is possible to determine the concentrations of various nutrients and salts within the plant and nutrient solution. LIBS is a robust analytical technique renowned for its rapid, multi-element detection capabilities with minimal sample

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preparation. The proposed system is adept at detecting and quantifying essential nutrients such as potassium (K), calcium (Ca), and magnesium (Mg), which are pivotal for plant growth and physiological functions.

This investigation aims to evaluate the effectiveness of LIBS as a tool for monitoring the nutritional status and salinity levels in hydroponic lettuce. Our results indicate that the LIBS system yields highly sensitive and reproducible spectra through direct analysis, obviating the need for traditional sample preparation methods. The system's ability to capture dynamic fluctuations in nutrient concentrations offers profound insights into nutrient uptake kinetics and early detection of potential imbalances. Specifically, we investigate the impact of different NaCl concentrations (0 ppm, 100 ppm, 1000 ppm) in the nutrient solution on lettuce plants and use LIBS to analyze the elemental composition of the plant leaves after a few days of exposure. By comparing the LIBS spectra across different treatments, this research aims to establish correlations between salinity levels and nutrient uptake, providing insights into the physiological responses of hydroponic lettuce to salinity stress. By facilitating remote and immediate analysis, LIBS empowers precise nutrient management, enhancing overall agricultural efficiency and productivity.

2 METHODOLOGY

The experimental setup for recording LIBS spectra is given in Fig. 1. A 1064 nm Nd-YAG laser (Quantel, Q-smart 850) was used, with the laser beam directed through a bi-convex lens with a focal length of 50 mm, focusing directly onto the hydroponic crop parts. Single-shot measurements were conducted with laser energy values ranging from 1.5 mJ to 3 mJ. Emission from the generated plasma was collected using a lens configured in a 180º backward geometry and transmitted to the slit of a Czerny-Turner spectrograph (Kymera 328i, Andor). All the parameters were maintained constant throughout the experiment, including a laser energy of 1.5 mJ, a gate delay of 900 ns, and a gate width of 500 ns.

Green lettuce seeds (Lactuca sativa L., Mikado variety) were sown in a sponge medium and germinated under controlled conditions, with temperatures maintained at 20°C to 24°C and relative humidity from 60% to 80%. The photoperiod was set to provide 16 hours of light per day. The experimental investigation was conducted in four distinct phases. The hydroponic nutrient solutions were prepared as a two-part mixture: Part A primarily contained calcium (Ca) and nitrogen (N), while Part B was a blend of potassium (K), magnesium (Mg), iron (Fe), and other nutrients. These solutions were mixed to achieve a pH range of 5.5 to 6.5 and an electroconductivity (EC) value of 1.8 to 2 $mS\cdot cm^{-1}$, providing optimal nutrition for the growth of lettuce crops.

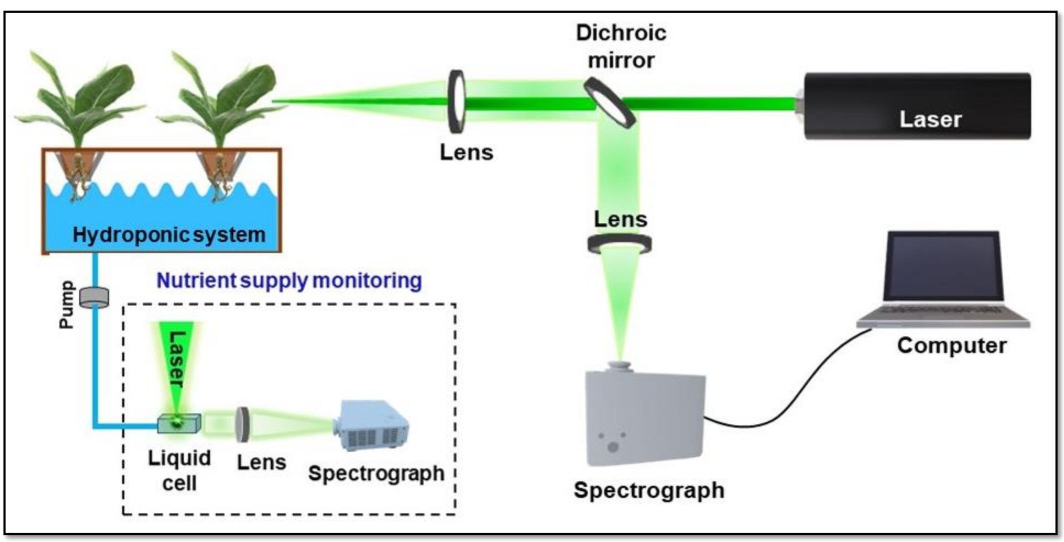

Figure 1 Experimental setup used for nutrient monitoring in hydroponics

In this investigation, lettuce plants were grown under controlled conditions and treated with nutrient solutions containing varying concentrations of NaCl for 7 days. The NaCl concentrations used were 0 ppm (control), 100 ppm (low NaCl), and 1000 ppm (high NaCl). Following this exposure period, LIBS was employed to directly analyze the elemental composition of the leaves from plants exposed to each NaCl concentration, assessing their nutrient uptake and response to salt stress.

3 RESULTS AND DISCUSSION

In our investigation, the LIBS spectra analysis revealed significant variations in sodium (Na) and potassium (K) uptake in lettuce leaves under different NaCl concentrations, highlighting the complex interactions between ions in hydroponic systems. Figure 2 (a-b) illustrates the LIBS spectra of lettuce leaves subjected to different Na concentrations. The Na emission peak at 588.5 nm was notably higher in the 1000 ppm Na treatment, indicating an increased Na uptake by plants exposed to high salinity. This increased uptake suggests that higher Na concentrations in the nutrient solution significantly enhance Na absorption. In contrast, the Na emission was considerably lower for both the A+B and 100 ppm Na treatments, reflecting reduced Na uptake under these conditions. This trend indicates that lower Na concentrations effectively limit Na absorption, maintaining a more balanced ion homeostasis.

Furthermore, the K emission peak at 766 nm exhibited an inverse relationship with Na concentration. The 1000 ppm Na treatment showed a substantial reduction in K uptake, as evidenced by the diminished K emission peak. This decrease can be attributed to the competitive inhibition between Na and K ions [7], as both ions vie for the same transport channels in plant roots. Consequently, high Na levels disrupt K absorption, leading to decreased K emission. Conversely, the K emission was more prominent in the A+B and 100 ppm Na treatments, where the competition for uptake was less intense, allowing for better K absorption. The comparison bar diagram (Figure 2c) effectively illustrates these trends, showing higher Na uptake in the 1000 ppm Na treatment and reduced K uptake under the same conditions. This visual representation confirms the adverse effects of high salinity on potassium absorption and highlights the plant's selective ion uptake mechanisms. This balanced ion uptake in the control treatment highlights the importance of maintaining optimal nutrient concentrations to support plant health and productivity. The analysis emphasizes that high salinity conditions, while promoting Na uptake, adversely affect the absorption of other essential nutrients like K, thereby highlighting the need for meticulous nutrient management in hydroponic agriculture.

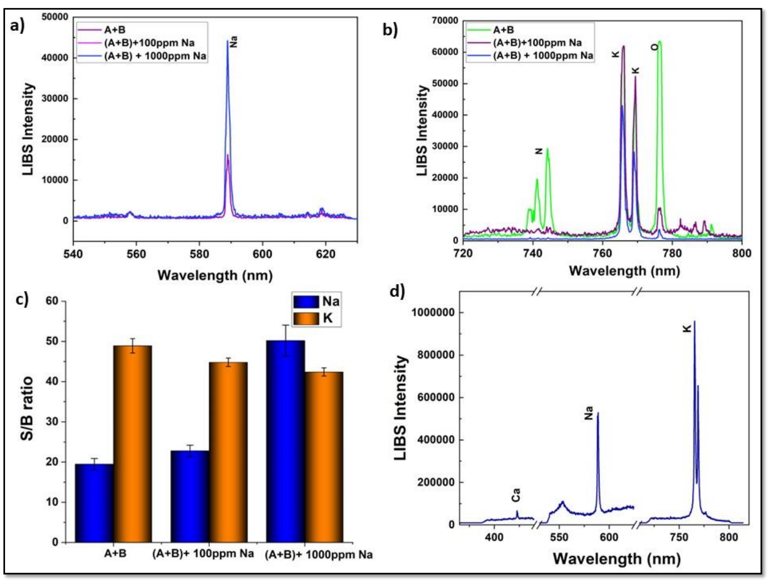

Figure 2 LIBS spectra of lettuce leaves under different Na concentrations, showing emission peaks: a) Na emission peak at 588.5 nm b) K emission peak at 766 nm c) Comparison bar diagram of Na and K uptake in lettuce leaves d) LIBS spectra of the nutrient solution using a liquid cell approach.

Additionally, Figure 2d shows the LIBS spectra of the nutrient solution using a liquid cell approach, demonstrating the detection of essential elements such as calcium (Ca), sodium (Na), and potassium (K). This capability of LIBS to monitor nutrient levels in real-time is crucial for the early detection of nutrient imbalances and stress conditions. By enabling preemptive nutrient management, LIBS technology supports the maintenance of optimal nutrient levels, enhancing plant health and productivity in hydroponic systems. This approach underscores the potential of LIBS to revolutionize nutrient monitoring in precision agriculture, promoting sustainable farming practices and optimizing resource use.

4 CONCLUSION

This investigation highlights the importance of managing salinity in hydroponic systems to maintain optimal nutrient balance and plant health. The use of LIBS for monitoring elemental composition offers a rapid and efficient method for assessing the effects of salinity on crops. By understanding the physiological responses of plants to salinity stress and implementing appropriate management strategies, hydroponic farmers can improve crop yield and quality, contributing to the sustainability and productivity of hydroponic agriculture. This work demonstrates the efficacy of LIBS as a robust tool for monitoring the nutritional status and salinity levels in hydroponic lettuce. Our findings revealed that Na uptake increased significantly in lettuce leaves treated with 1000 ppm Na, while it was lower for the A+B and 100 ppm Na treatments. Conversely, K uptake was reduced under high Na conditions but was higher for the A+B and 100 ppm Na treatments, highlighting the competitive inhibition between Na and K ions . The study also showcased the capability of LIBS to detect key elements such as Ca, Na, and K in the nutrient solution using a liquid cell approach, facilitating early detection of nutrient imbalances. This real-time monitoring capacity allows for preemptive interventions, optimizing nutrient management, and improving plant health and productivity in hydroponic systems. Overall, the integration of LIBS technology in hydroponics represents a significant advancement in precision agriculture, promoting sustainable farming practices through informed decision-making and optimized resource utilization. This research contributes to developing advanced monitoring techniques that enhance food security and resource use efficiency, supporting the broader goals of sustainable agricultural practices.

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