A microneedle-based Leaf Patch with IoT Integration for Real-time Monitoring of Salinity Stress in Plants

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***Abstract*—This work reports a novel microneedle-based leaf patch for real-time monitoring of sap pH levels, which is an early indicator of stress levels in plants. The leaf patch was interfaced with a data acquisition and processing unit to develop a low-cost, portable and field-deployable sap pH monitoring system. We demonstrated the application of this system in early detection and monitoring of the dynamics of soil salinity stress in a live cabbage plant.**

Keywords—microneedle sensor, leaf patch, sap pH, Internet-of-Things, salinity stress.

I. Introduction

Real-time monitoring of plant health is crucial for understanding individual plant's need to optimize yield and mitigate productivity losses. The traditional plant monitoring technologies involve collecting plant tissue samples through a destructive procedure, and then sending the samples to a laboratory for analysis [1]. This creates a delay between sample collection and analysis, thereby generating erroneous results. Analysis of tissue samples is valuable for studying plant diseases that further scientific knowledge but is not efficient for applications such as determining which plants need tending. Hence, it is important to monitor plant health in real time so that the growers can intervene immediately.

Variations in the sap pH indicate the state of plant health including risk potential for insect damage, foliage disease attack, nutritional imbalance, and stress levels [2, 3]. Environmental stresses cause a progressive change in the levels of secondary metabolites circulating in plants. Some key stress-associated metabolites include salicylic acid, abscisic acid, and amino acids, which are acidic in nature. These compounds are found in the xylem/phloem sap and their concentrations change in response to environmental stress conditions, resulting in a corresponding change in the sap pH level. Research demonstrates the use of leaf patches in multiplexed detection of volatile organic compounds [4] and physiological monitoring [5]. However, these sensors lack sap monitoring and rely on ligand chemical bonding, limiting their durability and lifespan. Additionally, they lack system-level integration and wireless data communication, thereby limiting cloud storage or end user applications.

This paper develops a minimally invasive, microneedle-based sensor patch for monitoring leaf pH levels in real time. An array of micron-size electrodes penetrated the leaf and provided electrochemical measures of pH level variations. The measured voltage was stepped up by a voltage booster to provide a detectable signal. The signal was then fed into a microcontroller to analyze and process the data and finally uploaded to the Internet-of-Things (IoT) cloud server. The data was finally visualized through the open source cloud platform Grafana, without being physically present at the experimental site. Fig. 1 illustrates a block diagram representation of the complete system. Moreover, data storage in the cloud allowed multiple users to monitor the plant health condition continuously and in real-time. In this project, the leaf sensing system was tested with a cabbage plant, but the patch can be easily reconfigured for a variety of other plants. The cabbage plants were subjected to different degrees of salinity stress and the measured sap pH levels were found to correlate with the amount of applied stress.

II. System Development

A. Microneedle Patch

The microneedle patch was designed using AutoCAD Fusion360 software and printed with FormLabs 3D printer using a bio-compatible resin. The patch was composed of two 2x2 arrays of microneedles. Each array was made on a 1cm x 1cm square base (inset of Fig. 2). The printed microneedles were pyramidal shaped with a square base of 900 μm, a height of 800 μm, and an angle of 30^0 at the tip. The patch had two trenches extending from the square base of the microneedle array to the edge of the patch for making conductive traces. Both the trenches ramped up at an angle to the base of the needles to provide a solid support for the conductive wires and prevent open circuits when the patch was bent, twisted,

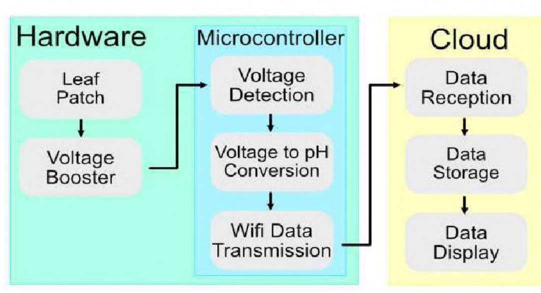

Fig. 1. Block diagram representation of the system

dropped, or otherwise mishandled. One microneedle array was coated with graphene to realize a working electrode while the other array was coated with Ag/AgCl to realize a reference electrode. Subsequently the patch was cured at 100°C for 60 minutes in an oven. The working electrode was coated with polyaniline (PANI) based nanofiber, sensitive to hydronium (H_3O^+) ions, following the recipe in [6]. The variations in the pH level were translated into changes in voltage values measured between the two electrodes.

B. Interfacing with the Microcontroller

The output voltage from the microneedle patch was stepped up 10 times by a voltage boost converter circuit comprising a 72 nH Inductor, a 1N4007G Diode, a 1.7 µF Capacitor, a 22 KΩ resistor, and an IRF540N MOSFET. The analog voltage was then converted to a digital signal by the in-built analog to digital converter in the ESP32 Wroom microprocessor unit. The microcontroller compared the measured voltage with a previously stored calibration curve to compute the corresponding pH value, which was sent to the InfluxDB database via Wi-Fi. A 555 timer was used to set the data acquisition frequency at 1 kHz. The whole system was powered by a 9V battery.

C. Interactive Data Visualization

The open source analytics and interactive visualization web application, Grafana, was configured to display the pH readings transmitted by the leaf patch to the cloud. The sap pH readings were displayed both in graphical and tabular formats, allowing the user to view different data formats on the same dashboard. Another feature was to allow the users to set an alert. For example, if the pH reading crossed a threshold, a notification was sent to the user's email address. The complete experimental setup is demonstrated in Fig. 2.

III. Results and Discussion

A. pH Sensor Calibration

The microneedle-based pH sensor was calibrated for sap pH levels ranging from 2 to 13. The calibration curve was generated by plotting the voltage measured across the microneedle array as a function of pH levels (Fig. 3a). The calibration curve is linear with a sensitivity of 2.92 mV/pH.

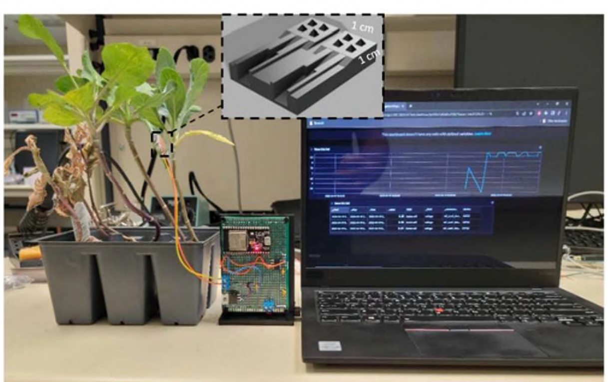

Fig. 2. Experimental setup of the complete IoT-enabled leaf patch. On the left side is the microneedle patch (inset) attached to the leaf of a cabbage plant. In the middle, the data acquisition and processing unit receives the voltage reading, amplifies it by the voltage booster, processes the measured signal by the ESP32 microcontroller, and transmits the data to the InfluxDB cloud system. On the right is the real-time pH graph displayed on a laptop.

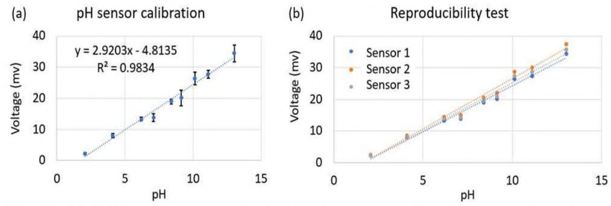

Fig. 3. (a) Calibration curve depicting the measured voltage as a function of sap pH levels. (b) Reproducibility test conducted with three identical sensors. Error bars show 3 repeated measurements.

B. Sensor Reproducibility

The microneedle sensors were also tested for reproducibility. In this regard, three identical sensors were tested with the same sap solutions spiked with varying pH levels. The sensors showed a very good reproducible characteristics with a coefficient of variance of <2% (Fig. 3b).

C. Real-time Salinity Stress Detection

The leaf pH monitoring system was tested in live cabbage plants under different levels of salinity stresses. Three different concentrations, i.e., 10 µM, 10mM, and 1M of 20 mL NaCl solutions were added to the soil and the sap pH levels were measured over 7 days. Measurements were taken four times a day, at 9AM, 12PM, 4PM, and 8PM. The results are shown in Fig. 4. The sap pH values decreased in response to the antioxidative defense response in the plant.

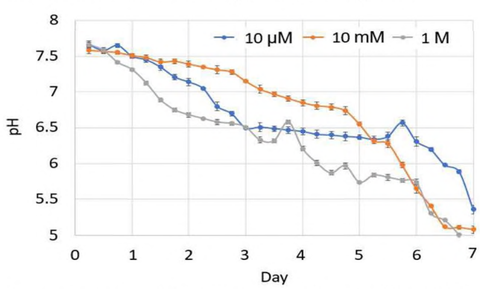

Fig. 4. Dynamics of sap pH for different levels of NaCl present in the soil.

IV. Conclusion

In conclusion, in this work we have designed and tested a new plant pH detection system with remote monitoring capability. The system was capable of monitoring the pH levels in response to salinity stress in real-time, thereby extending its application to remote monitoring of plant health.

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