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Zn-air Battery as Oxygen Sensor to Monitor Root Zone Oxygen Level in Plants

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ABSTRACT

Despite the expected high demands in the agricultural industry, the application of health monitoring systems for plants is still at the research level. While imaging methods are often used for monitoring the health status of the shoot part of a plant, there are limited parameters that can be measured for assessing the health status of a plant root. Studies show that roots need oxygen for aerobic respiration. Higher dissolved oxygen near the root zone may result in a more massive root and a healthier plant. Conventional oxygen sensors are designed to measure the oxygen level in a gaseous environment. Due to their bulky structure, their application for monitoring oxygen in the soil is challenging. In this study, we have used A10 zinc-air batteries as oxygen sensors to monitor the oxygen level at the root zone of four garden plants: sweet pepper, basil, tomato, and cherry tomato. Using a microcontroller system, the electric current from the batteries was recorded as a signal related to the oxygen level. The measurements indicate a variation of ~1% in the oxygen level every 24 hours when the plants were exposed to a controlled light for 12 hours and kept in dark for 12 hours. The simplicity of the application of Zn-air batteries allows us to monitor the oxygen level at several locations around the root of a plant to study their breathing through their roots.

Keywords: Oxygen sensing, Plant Health Monitoring System, Zn-air batteries, Root zone monitoring

1. INTRODUCTION

Food supply for astronauts is a serious challenge for long-duration space missions, particularly to the Moon, Mars, and beyond. A viable solution is to grow plants in space. Yet, our knowledge of how different plants grow in space is limited to a few species studied at the International Space Station (ISS). This is due to the fact that conducting experiments for growing various plants on the ISS is expensive and limited by the size of the growth chambers. Expanding the space plant biology research requires designing small and compact chambers equipped with advanced sensing and control systems only for remote human supervision. Such chambers can be launched into the earth's orbit to study the effect of microgravity, or sent to the moon and Mars for growing plants on their surfaces using extraterrestrial regolith instead of soil. Hence, NASA is interested in designing a CubeSat-size chamber for conducting experiments on growing plants in space. Addressing their needs, we are designing a 12U CubeSat system for monitoring the growth of selected spices inside the chamber. Since the health status of a plant can be evaluated through its appearance, our designed system used a digital camera for taking pictures regularly.

In our previous work, we focused on designing a system to collect information from the shoot part of green lettuce being grown in a chamber [1]. Our system consisted of an installed camera, a series of gas and VOC sensors, temperature, humidity, and light sensors. However, the growth of a plant largely depends on the growth of its root. An unhealthy root cannot absorb water and nutrients effectively. Consequently, the transpiration occurs more slowly resulting in slower growth of the plant and the production of less biomass. Regarding the limited resources (water, oxygen, CO_2, and nutrients) in space, the plant growing chambers should be designed for high yields and maximum production of biomass. Therefore, in addition to monitoring the health status of the plant through signals from its shoot, the chamber is required to be equipped with sensors to monitor the root section. The main challenge is the limited indicators that can be used. Although the shape of the root (distribution, its structure, root hairs, and root caps) is directly correlated with its health status, growing plants in soil or Lunar/Martial regolith (or regolith simulants), it is not feasible to take visual images of the root during the growth cycle of the plant. Therefore, other signals have been used. A common signal used for automated irrigation is to measure the moisture of the soil near the root. The moisture level can change due to a change in the environmental conditions, such as temperature or humidity. However, growing a plant in an isolated chamber, the soil moisture level directly represents the ability of the plant in absorbing water. Additionally, a healthy root requires enough oxygen at the root zone.

Studies show that the root zone oxygen level has a direct effect on the structure of the root [2]. Therefore, NASA is interested in monitoring the root zone oxygen level. A technical challenge is in the application of commercially available root zone oxygen sensors. Regarding their applications, the sensors are designed in the form of probes with a bulky structure suitable for insertion into the soil.

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Existing root-zone oxygen sensors are usually bulky and designed for monitoring the oxygen level a few inches deep into the soil [3, 4]. Considering the compact design of the chamber, the root compartment of the chamber does not have enough room to accommodate a large probe. Hence, a solution is required for measuring the oxygen level with a more compact device.

2. BACKGROUND

Gas sensors are designed mainly by using a material sensitive to a target gas. Based on the effect of the gas on the physical or chemical properties of the material, sensor devices may be designed to detect changes in their color, mass, dielectric constant, electrical conductivity, etc [5]. A common challenge in gas sensing is the selectivity of the active material to the target gas. An effective method for achieving high selectivity is to monitor the electrochemical redox reaction of the active material. Since oxygen can react with metals to oxidize them, the electrochemical detection method is a reliable approach. Each metal has a unique electrochemical redox potential through which the reactivity of the electrode can be monitored when exposed to oxygen. A commercial oxygen sensor may use a lead electrode as the sensitive material [6]. However, because an electrochemical cell requires an electrolyte, it is essential to have a membrane to allow gas diffuses into the cell. Figure 1.a and b show the structure of two different electrochemical gas sensors known as potentiostatic and amperometric cells [6]. A potentiostatic cell monitors the redox reaction on the active electrode (working electrode) when a constant voltage is applied between the reference and the working electrode through an external circuit. The variation in the oxygen concentration then affects the current from the sensor. In contrast, an amperometric cell is a simple two-terminal electrochemical device. According to the Nernst equation when the concentration of oxygen (as the reactive material to the active electrode) changes, the potential of the electrode changes resulting in a change in the electromotive force across the cell [7]. To monitor the oxygen concentration, the output of the cell is connected to a resistor to allow charges to circulate through the cell. Monitoring the current through the resistor, the concentration of the oxygen can be estimated. It should be mentioned that a critical part of a gas sensor is the design of the active electrode to be able to interact with the target gas molecules while making an electrode-electrolyte interface. Also, the membrane in sensors are designed to allow gases to diffuse into the cell but limit the evaporation of the electrolyte from the cell.

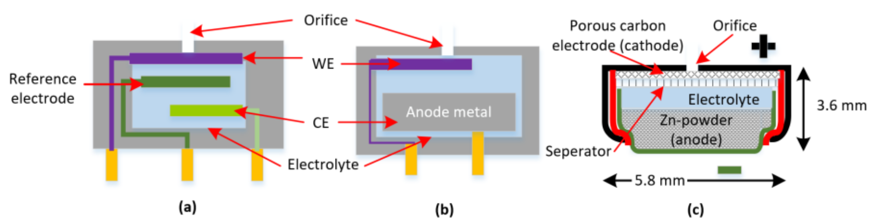

Figure 1. Schematic of (a) potentiostatic and (b) amperometric gas sensors. (c) cross section of an A10 Zn-air button cell battery.

Considering the mechanism of operation in Zn-air battery, the cell is essentially an amperometric oxygen sensor [8]. Figure 1.c shows the structure of a Zn-air battery. The cell is consisted of a zinc anode, a porous carbon electrode acting as the cathode while allowing oxygen to diffuse into the cell, an aqueous-based electrolyte, and a separator. When a current is passing through the cell, at the cathode we have [8]:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (E^0 = 0.4\,V) \qquad (1)$$

At the anode, zinc oxidizes:

$$2Zn + 4OH^- \rightarrow 2ZnO + 2H_2O + 4e^- \qquad (E^0 = 1.25\,V) \qquad (2)$$

Overall:

$$2Zn + O_2 \rightarrow 2ZnO \qquad (E^0 = 1.65\,V) \qquad (3)$$

While, due to the diffusion limited mechanism of allowing oxygen to enter the cell, the voltage of the cell is not much sensitive to the variation in the oxygen concentration, the electric current generated by the battery is a function of the oxygen concentration (i.e., partial pressure of oxygen) [8]. For effective usage of a Zn-air battery as an oxygen sensor, it is required to conduct experiments for the calibration of the sensor. Still, a main concern in using Zn-air battery as a root-zone oxygen sensor is the durability and sensitivity of the device to the oxygen variation in the new application. Therefore, this study was conducted using off-the-shelf Zn-air batteries in the soil of four different plant. A reference cell and a calibrated potentiostatic oxygen sensor was also used as the reference to the batteries inside the soil.

3. METHODOLOGY

3.1 Materials and Equipment

The light source was a LED Grow Light Tube purchased from Amazon. The light source was made up of 576 LEDs (96 red, 72, blue, 288 warm light, and 120 white) generating high photosynthetic active radiation (PAR) for indoor plants. The combination of LEDs mimics the spectrum of the standard PAR. Size 10 (A10) Zn-air batteries (diameter of 5.8 mm and thickness of 3.6 mm) were purchased from Amazon. The tag was kept on the orifice until shortly before using the battery in the circuit. Gravity Potentiostatic oxygen sensor with the I^2C interface, DHT11 humidity sensor, and 10 kΩ light dependent resistor (LDR) were purchased from Amazon. Teensy 3.6 development board was bought from PJRC. Plants were purchased from Lowe's.

3.2 Experimental Setup

The commercially available button cell battery holders require a casing. To expose the battery, a simple design was applied on a printed circuit board (PCB) for easy insertion into the soil. Since batteries cannot be soldered, as shown in Figure 2.a, wires were soldered to the PCB to pass over the battery and make contact with the positive terminal. The wires were bent to get sure that the orifice is not blocked while making reliable electric contacts. A 10 kΩ resistor was connected to the terminals of the battery to run it in the amperometric mode. The resistor value was selected based on the capacity of the battery (~189 mAh). With a typical voltage of 1.45 V, the battery was draining with an average current of 0.145 mA. Four soil sensors were made and connected to the analog to digital converter ports of the microcontroller. Another battery was used as the reference next to the Gravity oxygen sensor. The circuit was also equipped with a humidity and a light sensor. The circuit diagram of the setup with a picture of it is shown in Figure 2. The microcontroller was programmed to record data from all sensors every five seconds. The soil sensors were inserted into the soil of four different pots each with one of the plants (basil, cherry tomato, tomato, green bell pepper). The selected plants are identified by NASA as potential plants for growing in space.

3.3 Experimental method and data collection procedure

The experiments were conducted indoors using a programmable PAR lighting system isolated from ambient light. The indoor experiments were conducted for one week and the light source was programmed for 12 hours of illumination and 12 hours of dark. After the indoor test, the setup was moved outside while collecting data for 5 days. A picture of the setup is shown in Figure 2.c. The recorded data on the SD card of the microcontroller was transferred to a computer once a day. Also, the plants were watered regularly every day.

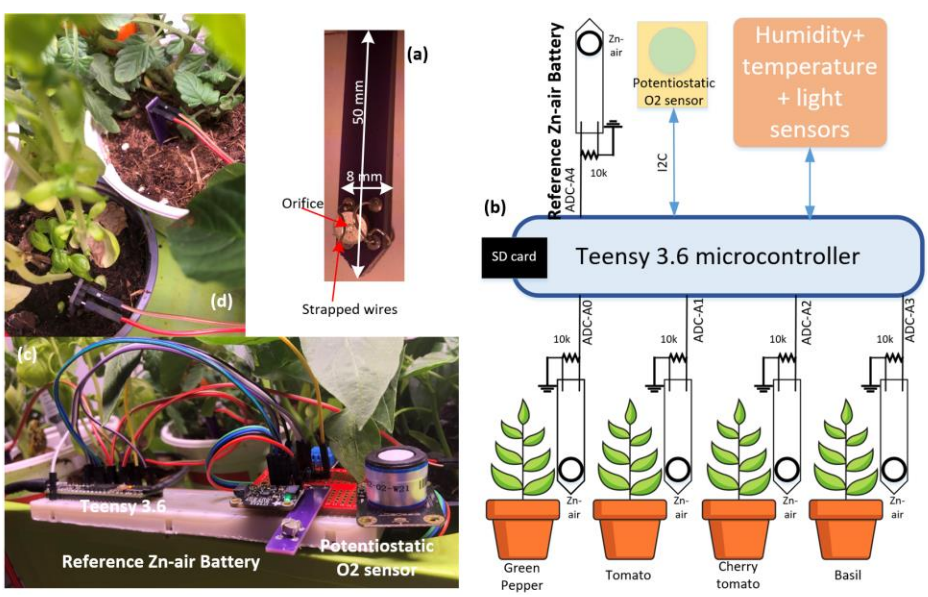

Figure 2. (a) PCB design to hold the batteries. (b) schematic of the setup. (c) a picture of the setup. (d) a picture of the sensors being inserted into the soil of the pots.

4. RESULTS and DISCUSSION

The circuit with the oxygen sensor and the reference battery was tested for 24 hours when the setup was located outdoors. Figure 3 shows the battery voltage and the signal from the oxygen sensor. Unlike the signal from the potentiostatic oxygen sensor, the battery voltage had a high frequency "noise" with an amplitude that sometimes exceeded 0.04 V. Nevertheless, on average, the battery voltage was following the trend in the oxygen concentration. The source of the noise is not clear to us. It is possible that the contact resistance through the strapped wire was fluctuating. A noticeable fact about the data is the signal from the oxygen sensor showing the change in the oxygen concentration from 21.5 % to 22.8% and random variation in that range. This is likely due to the storm with lightning on the day of the experiment.

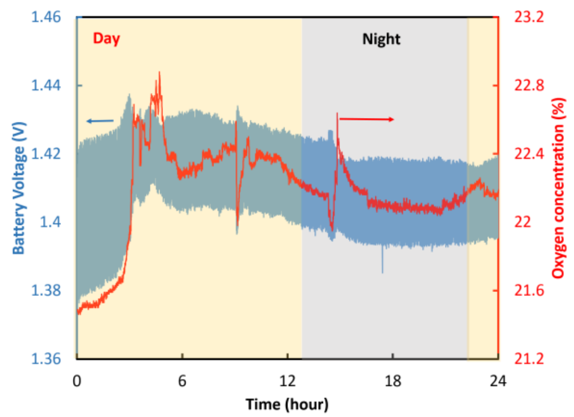

Figure 3. Voltage from the reference battery and the recorded signals from the oxygen sensor. The setup was tested outdoor in a stormy day on June 15, 2023 (Tampa, Florida).

The system was then transferred to indoor and the probes were inserted into the soil of the plants. For the indoor study, the plants were exposed to the LED PAR light for 12 hours of illumination and 12 hours of dark. Figure 4.a shows samples of measured oxygen levels in the soil of the basil and tomato in a 24-hour cycle of the experiment. The data shows that the average battery voltage from the device in the tomato soil was ~1.32 V while it was 1.30 V in basil. Although this might be an indication that the oxygen level in basil soil was less than that in tomato, the state of charge in each battery can be different resulting in an offset voltage. The sudden voltage drop at the 9^{th} hour for the basil sample occurred when the plant was watered. It is likely that water may have penetrated into the cell through the orifice or shorted the circuit between the battery terminals momentarily. Studying data from the same sample on other days did not show this effect. The zoomed data in Figure 4.b shows almost the same 0.04 V noise amplitude in light, but the noise level in dark was much less. The change in the noise level had a strong correlation with light and was repeated over the course of a week of testing different samples. The oxygen sensor and the reference battery out of the soil did not show any specific correlation with light. Hence, we may conclude that during the photosynthesis process (under light) the oxygen level in the soil fluctuates more significantly than that during dark time. Analyzing the results from all the samples during the seven days of the experiments, no specific relationship between the amplitude of the fluctuated battery voltage in light with the type of plant was observed. However, as shown in Figure 5, on day 6, the voltage of the battery in the pepper soil dropped to an average of 0.18 V. The light and dark response was still clear at this stage indicating that the electrochemical cell was active despite the large voltage drop. This again can be due to watering the sample a day before.

After seven days the plants were moved outdoors while the data collection was continued. Due to large variation in temperature, humidity, light intensity, and even atmospheric oxygen level (due to random lightning), no specific correlation between the battery signals and other factors were found. However, after a significant storm on day 13 of the experiment, the electronics failed and the experiments were stopped. Batteries were removed from the soil and inspected. The battery looked healthy and the voltage was 1.45 V, but there was some corrosion around the PCB soldering points due to the interaction with the soil. The results reflect the challenges in using Zn-air battery for oxygen monitoring at root zone. A custom designed battery holder may be needed for long term study of plants.

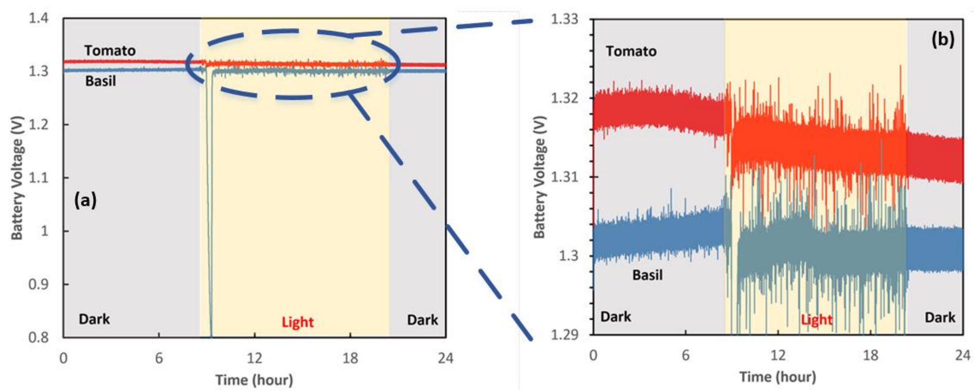

Figure 4. (a) Recorded battery voltages from tomato and basil plants on day 3 of the experiment. (b) Zoomed graph of the measured voltages showing the large voltage fluctuations during illumination period.

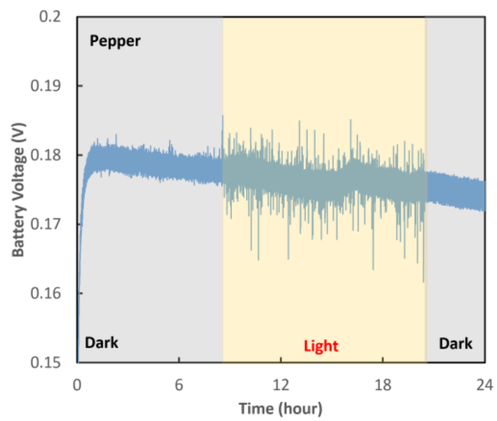

Figure 5. Recorded voltages from the battery in the pepper soil on day 6 of the experiment.

5. CONCLUSION

The results from this study show that monitoring the oxygen level at the root zone with a Zn air battery is feasible but challenging. The results clearly show that during the photosynthesis process, the dynamic of oxygen absorption by the root is very different than that during the dark time, regardless of the type of the plant. Further studies in this field is required before designing a system that can be used for the efficient growth of various plants in space.

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