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Smartphone near infrared monitoring of plant stress

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ABSTRACT

The most widely used method for monitoring plant stress is the use of near infrared (NIR) spectrophotometry to calculate normalized difference vegetation index (NDVI), as defined by [NIR reflectance − red reflectance]/[NIR reflectance + red reflectance]. NDVI measures the chlorophyll absorption in the red spectrum relative to the scattering by cellular structure in NIR, and has been used to monitor vegetation health and subsequently its stress from aerial or satellite images. Rather than using an NIR spectrophotometer or an NIR camera that is rather expensive, we attempted to use a commercial smartphone, utilizing its (potentially unintended) ability in recognizing near infrared (NIR) color. Some of the most recent versions of smartphones have eliminated the NIR block filters on their cameras, and able to recognize NIR in their red pixels of CMOS array. Through attaching an inexpensive high pass filter at 800 nm to a smartphone camera, we were able to collect the NIR reflectance (with a high pass optical filter) and the red reflectance (without a filter), enabling NDVI assessments. This method was verified by measuring the NDVI values from a series of chlorophyll solutions, and showed a strong linear correlation with $R^2 = 0.948$, corroborating the smartphone's ability in evaluating NDVI. Using the leaves from three different plant species, the NDVI values were evaluated using the smartphone and compared with the plants' chlorophyll contents using acetone extraction and subsequent spectrophotometry. A good linear relationship was found with $R^2 = 0.88–0.92$. We further evaluated the NDVI values against the plants' water contents (measured by oven-drying), showing the non-linear relationship with the NDVI saturation above 50% water content. The assay time was almost instantaneous, requiring only a smartphone and a high pass filter, thus allowing inexpensive, easy-to-use, rapid, and early prediction of plant stress that can be used for field and household applications.

1. Introduction

Chlorophyll is a pigment that exists in the chloroplasts and plays an essential role for photosynthesis, a well-known growth method for plants. Chlorophyll content per leaf area can serve as an indicator for plant health and subsequently plant stress (Steele et al., 2008). One of the majority of plant stress is attributed to water stress (Blum, 2018).

Diverse research has been conducted to evaluate the health and stress in plants. Early attempts include automated machine vision (Kacira et al., 2002), focusing on green coloration under controlled environments. However, green reflectance is much weaker than near infrared (NIR) or infrared (IR) reflectance and can vary significantly by ambient conditions, thus may not provide accurate information on the plant stress. IR based thermal imaging has also been attempted to monitor plant water stress. Originally developed for mapping temperature distribution of an object, it can also be used to evaluate the plants' water content due to the strong IR absorption by water (Meron et al., 2010). However, IR thermal imaging cameras are still expensive (although their price has dropped significantly in the last decade), and the results are greatly affected by environmental temperature and humidity. Hyperspectral imaging has also been used to better quantify plant stress (Kim et al., 2011), but this method requires integration of multiple cameras and sensors (or an expensive ready-to-use equipment) to acquire sufficient amount of data.

As mentioned above, green color is reflected the most by plant leaves, providing characteristic green color for healthy plants, due to the chlorophyll's absorption in blue and red color. While green reflectance is usable, NIR and IR based methods provide much better results in monitoring plant health and stress (especially by water) (Peñuelas and Filella, 1998). In recent decades, normalized difference vegetation index (NDVI) has been utilized as a major indicator for the health status of plants and green biomass (e.g. algae), and indirectly their water contents (Rouse, 1973). It is based on the difference between the plant's red reflectance (*Red*) due to the pigment absorption

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by chlorophyll and the NIR reflectance (*NIR*) due to the scattering by cellular (spongy mesophyll) structure, which is defined as $NDVI = (NIR - Red)/(NIR + Red)$ (Tucker, 1979). There are many studies reporting that NDVI has a linear relation with rainfall (Aguilar et al., 2012), with temperature (Wang et al., 2003), and with evapotranspiration (Groeneveld, 2008), as well as with water stresses (Kim et al., 2011; Zhao et al., 2015).

Despite these merits of NDVI spectrophotometry and imaging, it still requires an NIR spectrophotometer or an NIR camera, which can be expensive. If a smartphone camera can be used, it will provide a simple and low-cost alternative to an NIR camera, for use in small farms or residential homes. However, no such study has been demonstrated until now, due to the difficulty in capturing NIR using a smartphone camera. Even if a smartphone can recognize NIR, these intensities will be added to those considered red intensity (closest wavelength). This makes it difficult to differentiate NIR reflectance from red reflectance in smartphone images. Recent smartphones, e.g. iPhone 5 through 7, used an NIR block filter to eliminate the NIR influence. However, the most recent smartphones, such as iPhone 8 or Galaxy S8, do not use such NIR block filter (experimentally confirmed in this study), presumably to lower the unit price, or potentially to use in conjunction with facial recognition feature. This elimination of an NIR block filter can be exploited as an advantage towards NDVI measurement. While both NIR and red reflectance are recognized by the red pixels in a smartphone camera, it is possible to make a distinction by capturing two images, one with an 800 nm high pass filter (for NIR reflectance) and the other without (for red reflectance). A high pass filter at 800 nm will eliminate all wavelengths below NIR and the resulting smartphone images should represent only the NIR reflectance.

The aim of this study is to demonstrate the use of a smartphone for NDVI acquisition for rapid diagnosis of leaf health and stress. Three different species of plants, Japanese mock-orange cheesewood, Red gum eucalyptus, and Tea rose, were tested, which are very popular shrubs for landscaping in southern Arizona. They can resist heat and drought to a certain extent while requiring constant supply of drip irrigation, serving as optimum models for monitoring plant health and stress. The smartphone acquired NDVI values were compared to a standard analysis of the chlorophyll solutions and the extracted chlorophylls from plant leaves.

2. Materials and method

2.1. Various smartphones' abilities in recognizing NIR

Eight different smartphones were tested in this experiment to find the most appropriate model: Galaxy S7 and S8 (Samsung Electronics, Co., Ltd., Seoul, South Korea), Nexus 5X (Google LLC, Mountain View, CA, USA), iPhone 5, 6S, SE, 7 and 8 (Apple Inc., Cupertino, CA, USA). Each smartphone's ability to capture NIR was tested using an 850 nm LED (L3-0-IR5TH50-1, LEDSupply, Randolph, VT, USA) as well as a 940 nm LED (L2-0-IR5TH30-1, LEDSupply). Both LEDs were powered with 5.75 V, using a 200 Ω protective resistor. The voltage drops were 1.39 V for 850 nm LED and 1.23 V for 940 nm LED, and currents were 21.8 mA for 850 nm LED and 22.6 mA for 940 nm, all of which are within normal operating conditions as specified by the manufacturer. These smartphones captured the images 10 cm away (the closest distance with optimum focusing) from these NIR LEDs in a dark room, using shutter time = 1/8 s, white balance = 4500 K, and ISO = 400.

2.2. Chlorophyll solutions

Chlorophyll *a* (479–61-8, Sigma-Aldrich Corp., St. Louis, MO, USA) was dissolved into 96% ethanol to make 10, 20, 40, 60 and 80 μg/mL solutions. These solutions were placed in plastic containers, on top of a white paper as a consistent background, for the smartphone based NDVI measurements.

2.3. Chlorophyll extraction and spectrophotometric quantification from plant leaves

Three different plant leaves were tested in this experiment: Japanese mock-orange cheesewood (*Pittosporum tobira*), red gum eucalyptus (*Eucalyptus camaldulensis*), and hybrid tea rose (*Rosa* sp.). Plants were obtained from the University of Arizona main campus. 9 to 11 leaves were acquired for each plant; roughly three healthy (green), three half-dried (yellow-green), and three dried (yellow) leaves. After measuring the NDVI values using a smartphone, 100% acetone was applied to these leaves to extract chlorophyll. The solutions were analyzed using a miniature spectrophotometer (USB4000, Ocean Optics, Inc., Dunedin, FL, USA) following the equation by Lichtenthaler (1987).

2.4. Water contents of plant leaves

42 leaves were acquired for each plant species. To calculate their water content, the weights of all leaves were measured using an electronic balance (0.1 mg accuracy; model number AR2140; Ohaus Corp., Pine Brook, NJ, USA), followed by drying them in full in an oven (model number 1321F; Sheldon Manufacturing, Inc., Cornelius, OR, USA) at 100 °C and re-measuring their weights. To ensure all leaves are fully dried, dried weights were also measured after 15 min, 30 min, 1 h, 2 h, 3 h, and 4 h. Dried weights did not change by two times the balance' accuracy, i.e. $< 0.2 \pm 0.1$ mg, corresponding to 95% confidence interval, after 3 h for all leaves tested, which were used as bases for calculating their water contents.

2.5. NDVI measurements using a smartphone and an NIR filter

Leaf images (or the images of chlorophyll solutions in container) were taken with the Galaxy S8 smartphone camera with and without an 800 nm high pass filter (catalog number FEL0800; Thor Labs, Newton, NJ, USA). Leaves (or chlorophyll solutions) were placed on a white paper, providing a consistent background. The images without the filter were used to measure the red color reflectance (*Red*) and the images with the filter were used to measure the NIR reflectance (*NIR*), as illustrated in Fig. 1. The smartphone was positioned 10 cm away from the leaf to allow optimum focusing, and at 45° from the leaf that minimized the non-specific reflection and the shadow of the smartphone itself.

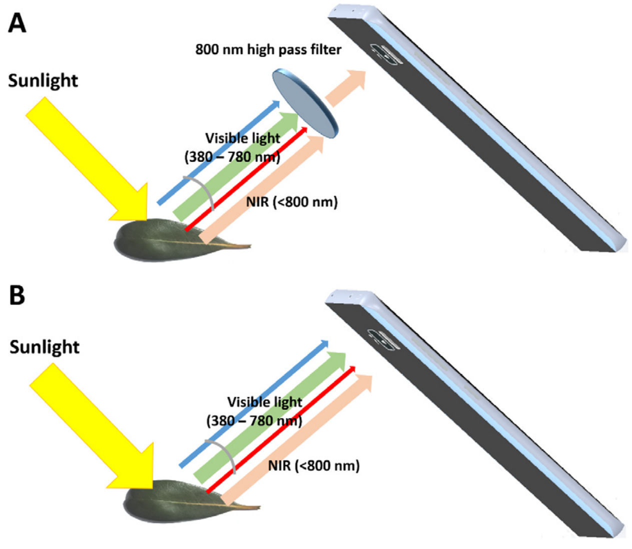

Fig. 1. Schematic illustration of smartphone based NDVI measurement. (A) An 800 nm high pass filter is used to obtain the NIR reflectance (*NIR*). (B) Without the high pass filter, all visible lights are captured in a smartphone camera, which is used to measure the red reflectance (*Red*).