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A LOW-COST INTEGRATED NIR SPECTROMETER FOR CHLOROPHYLL CONTENT INDEX MEASUREMENT

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ABSTRACT

Chlorophyll sustains plants as it is one of the vital components in the photosynthesis process. Chlorophyll content in the leaf indicates the health of the plants and it can be used as an indicator for fertilizer requirement, in particular for Nitrogen management, in the growing cycle of certain crops. Chlorophyll measurement is required for the growers to monitor and make decision for fertilization schedule. The measurement is also needed for plant scientists. Chlorophyll meters are used to measure the relative chlorophyll content index in the leaf either by chemical process, image processing, or spectroscopy technique. In general, chlorophyll meters are expensive. This work proposes a low-cost meter to measure the chlorophyll index by exploiting the newly-developed near-infrared spectrometer. The NIR spectrometer is an optical MEMS sensor having 6 channels spanning from 610nm to 860nm. The simple prototype was built by using the common Raspberry Pi to collect data from the spectrometer. Fifteen leaf samples from various tree types were measured and data were analyzed. The results were compared with the commercial hand-held device, the SPAD-502. An average error of 7.84% was obtained using the designed meter. Off-the-shelf components provide a fraction of the cost of the high-end meters for an acceptable chlorophyll content index reading.

Keywords: chlorophyll content index meter, near-infrared spectrometer, low-cost sensor.

INTRODUCTION AND BACKGROUND

Chlorophyll (CL) is green pigments and it was isolated in 1817 by Joseph Bienaimé Caventou and Pierre Joseph Pelletier. Chlorophyll is derived from the Greek words, chloros ("green") and phyllon ("leaf") [1]. Chlorophyll is concentrated within organisms in structures called chloroplasts. The function of the majority of chlorophyll (up to several hundred molecules per photosystem) is to absorb light energy and transfer to other parts of the photosystem [1]. Chlorophyll is essential in photosynthesis which is a chemical reaction that takes place inside a plant, producing food for the plant to survive. Water (from the soil), carbon dioxide (from the air) and light (from the sun) are essential for the photosynthesis to happen with the participation of chlorophyll. There are two main types of chlorophyll: chlorophyll: a absorbs energy from wavelengths of blue-violet and orange-red light while chlorophyll b absorbs energy from wavelengths of blue and red lights as shown in Figure-1. Both chlorophylls absorb energy from the visible spectrum of light. High levels of chlorophyll usually indicate that the leaf is high in nutrients, usually nitrogen and phosphorous [2].

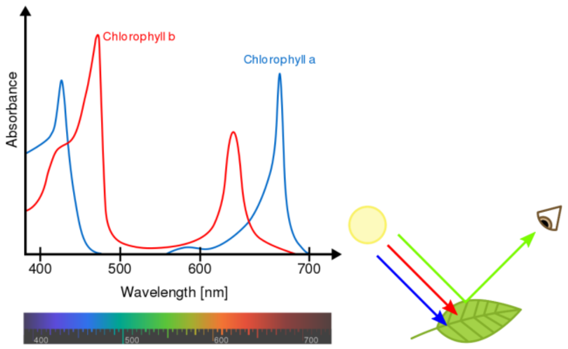

Figure-1. Chlorophyll absorption spectrum of the green leaf [3].

The accurate method to determine chlorophyll in the leaf is the use of chemical analysis called high-performance liquid chromatography (HPLC) [4]. This is a standardized method but the technique is complicated, expensive, time consuming, and can only be performed in the laboratory settings. With the advanced technology, different methods have been developed in which one is the use of image processing to estimate the chlorophyll level [5]. Spectrometer is the common technique based on the absorption and transmission characteristics of the chlorophyll to various energy wavelengths from the light [6,7]. A spectrophotometer is used to measure the amount of light absorbed or transmitted by the sample. The instrument operates by passing a beam of light through a sample and measuring the intensity of light reaching a detector. The beam of light consists of a stream of photons and they are absorbed by the chlorophyll. This absorption reduces the number of photons in the beam of light, thereby reducing the intensity of the light beam that is received and measured at the detector [8,9].

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Commercially available handheld meters are used in the field for different purposes from scientific research to normal use by the growers. These chlorophyll meters (CMs) dominate in the market are developed based on the spectroscopy principle. Measuring and monitoring the chlorophyll in the leaves is very important to farmers as they can schedule fertilizing in the most efficient way in the growing cycle. This is based on the fact that CL in the leaf is strongly related to the Nitrogen status of the plants [10, 11, 12]. Most CMs determine relative leaf CL content, called chlorophyll content index (CCI), by measuring absorbance and transmittance, by the leaf, of red radiation, which CL absorbs, and near infra-red (NIR) radiation, which CL transmits [13,14]. Higher values of CM readings are resulted from the increment in absorbance of red radiation by the chlorophyll. Transmittance-based meters are most common in commercial CMs and one of them is the SPAD-502 meter (Konica Minolta, Japan). Table-1 shows the small list of various CMs in the market.

Table-1. Characteristics of leaf chlorophyll meters [11].

Device	Measuring principle	Wavelengths (nm)	Units
SPAD-502	Transmittance	650, 940	SPAD units
atLEAF+	Transmittance	660, 940	atLEAF units
MC-100 Chlorophyll Conc. Meter	Transmittance	653, 931	CCI
MULTIPLEX	Fluorescence	635, 685, 735	SFR_R
MULTIPLEX	Fluorescence	516, 685, 735	SGR_G

Figure-2 shows the principle of the Soil Plant Analysis Development (SPAD) system to measure CCI. The SPAD meter determines the relative amount of chlorophyll present by measuring the absorbance of the leaf in two wavelength regions (653nm and 931nm). SPAD is the most popular CMs in the market and it has been widely used in academic and industries [15,16]. Increasing SPAD values indicates higher concentrations of chlorophyll per leaf unit area. As shown in Table-1 and Figure-1, the transmit spectrum of chlorophyll is in the infrared region, not restricted to the 931nm wavelength.

The work presented in this paper describes a compact CCI measuring device comparable to the SPAD system. The designed system uses newly-developed optical components which significantly reduce the cost of the device.

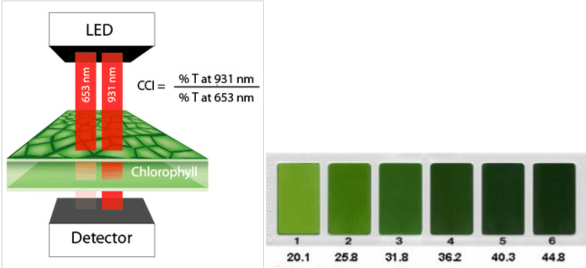

Figure-2. CCI measuring of SPAD [12].

METHODOLOGY AND SYSTEM DESIGN

The designed system is based on spectroscopy principle to measure the content of chlorophyll in the leaf. Although the measuring method is similar to the one shown in Figure-2 but we use different wavelengths. Figure-3 depicts the proposed system. The light source is a white color LED. This LED when turned on will provide a wide spectrum of light including the near-infrared region. The beam light passes through the sample and lands on the spectrometer. The small spectrometer specifically detects the red color and 5 other wavelengths in the NIR spectrum. The spectrometer provides data for 6 different wavelengths and the data are post-processed to calculate the CCI and finally converted into equivalent SPAD units. As shown in Figure-3, the prototype system consists of two main parts. The first section is the sensing and the second is the data collection.

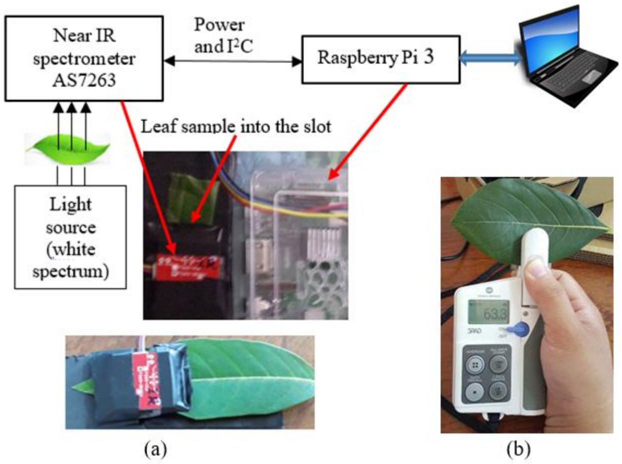

Figure-3. (a) System overview and device prototype. Leaf samples are placed in the slot between the light source and the spectrometer. (b) SPAD-502 is used for comparison purpose.

The most important component in the system is the compact, low cost, advanced technology system-on-chip spectrometer, the AS7263 made by AMS [17]. This highly integrated device delivers a 6-channel multi-spectral sensing in the near-infrared wavelengths from approximately 610nm to 860nm with full-width half-max of 40nm as shown in Figure-4. An integrated LED driver with programmable current is provided for electronic shutter applications. Control and spectral data access is

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implemented through either the I²C register set, or with a high level AT Spectral Command set via a serial UART [17]. In this design, the I²C communication between the spectrometer and the Raspberry Pi (RP) is used for controlling the spectrometer and data collection.

A 3.3V DC power supply to the sensor is provided by the RP. As seen in Figure-3, the white light passes through the leaf sample and enters the opening of the sensor. Optical components in the sensor breakdown 6 wavelengths striking on the photo-detectors and the photodiode voltages are processed and converted into light intensities in counts/(µW/cm2).

Raspberry Pi is a common single board computer. The RP has ample computing power and peripherals for many practical applications including IoT and embedded systems. In this sensor prototype, the third model of RP is used to provide power to the sensor and establish the I²C communication link to the AS7263.

As described earlier, the chlorophyll in the leaf sample absorbs red light and passes the NIR spectrum. The white light source provides these spectra to the sample. The useful measurement data from the spectrometer are the intensity of "red" and other 5 channels in the NIR region. Every second, the NIR spectrometer AS7263 sends 3 sets of 6 numbers representing the amplitude of 6 channels in its NIR spectrum range shown in Figure-4.

The RP is programmed (in Python) to receive and save data into a file (in Excel format) while the sensor is in operation. Data files are then transferred to a computer for viewing and processing. Processing data provides 6 levels of the spectra in NIR which the leaf sample partially absorbs (i.e., absorption rate) or partially passes through (i.e., transmission rate).

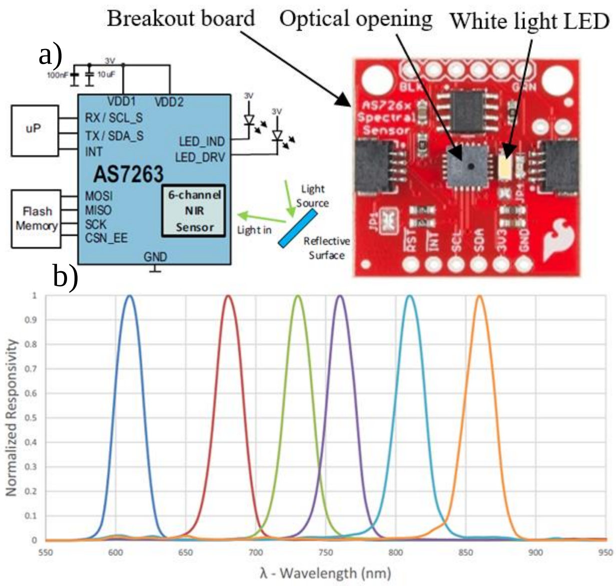

Figure-4. NIR spectrometer AD7263: (a) Block diagram and breakout board. (b) Typical optical characteristics (normalized intensity) [17].

EXPERIMENTAL RESULTS

The prototype was built and tested. As described, the white LED is turned on to provide a wide spectrum of the light beam. The beam passes through the sample and its intensity is detected by the spectrometer through its opening. The amplitude of each channel depends on the level of absorption/transmission of the sample to specific wavelengths. The spectrometer measures the intensity of 6 channels in counts/(µW/cm2) and sends the data to the RP. Fifteen different leaf samples were used, and each sample had 410 readings on the absorption of the leaf samples to all 6 channels. On each of the 15 samples, data from the spectrometer without sample were also recorded for calculating the transmission rates. The readings from the SPAD-502 were also recorded for all 15 leaf samples.

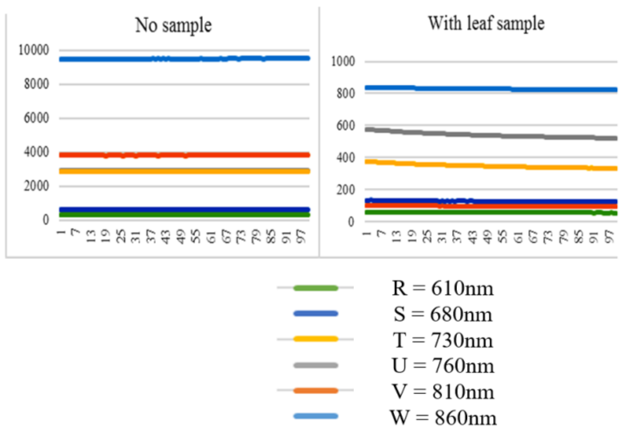

Figure-5. Absorption/transmission NIR spectra of no-sample and of leaf-sample show partial spectra absorbed by the sample.

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Figure-5 shows an example of the measurement results (absorption/transmission) of the tests on leaf samples. As seen on the “No sample” plot, without the leaf sample in the slot, the spectrometer receives the full intensity of its NIR spectrum. After the leaf sample was inserted into the slot, chlorophyll and other substances inside the leaf partially absorb these spectra and the spectrometer values are much lower. Higher absorption by the leaf results in lower number of photons striking on the photodetector and vice versa, higher transmission rate provides higher number of photons striking on the detector.

Table-2. Sample of collected data of a jackfruit leaf transmission on 6 channels (counts/(uW/CM^2)).

Detection at different wavelengths from the AD7263 spectrometer					
610nm	**680nm**	**730nm**	**760nm**	**810nm**	**860nm**
1579.00	166.77	1797.07	1232.21	427.72	168.63
1576.27	166.77	1784.52	1224.21	426.68	167.43
1580.37	167.81	1785.66	1225.21	428.76	167.43
1585.84	167.81	1786.80	1225.21	427.72	168.63
1588.57	166.77	1782.23	1221.22	427.72	168.63
1592.67	166.77	1781.09	1220.22	426.68	167.43
1589.94	165.73	1768.54	1210.22	423.57	167.43
1595.41	164.68	1768.54	1208.23	422.53	166.22
1600.88	165.73	1770.83	1209.22	423.57	167.43
1598.14	164.68	1761.70	1201.23	425.64	166.22
1609.08	164.68	1767.40	1205.23	422.53	167.43
1643.26	167.81	1797.07	1225.21	428.76	169.84
1636.42	167.81	1782.23	1213.22	433.95	168.63
1611.81	164.68	1754.85	1193.23	423.57	165.02

Figure-6. Ochna tree leaf (sample #8) and Country almond tree leaf (sample #1).

Table-2 shows an example of the collected data. In this table, six channels of the AD7263 spectrometer provide the light power of 6 wavelengths from 610nm to 860nm of a fully-grown jackfruit leaf. The 610nm wavelength is the Red light in Figure-2 which the chlorophyll absorbs. The other five are the wavelengths at which the chlorophyll (and other substances) in the leaf allow the light passing through (transmission). The other substances also absorb certain wavelength in the NIR region therefore the transmission rate does not indicate the full transmission of the chlorophyll. Figure 6 illustrates the data collection of Table-2. The waveforms depict the transmission (or absorption) level of the leaf to each of the 6 wavelengths. The highest transmission belongs to the 730nm wavelength. The highest absorptions are the 680nm and 860nm wavelengths.

From the collected data, transmission rate and CCI were calculated using the following equation:

$$CCI = \frac{\%T\ at\ different\ wave\ length\ (\lambda n)}{\%T\ at\ Red\ color\ (610nm)} \quad (1)$$

where T is transmission rate:

$$\%T\ at\ \lambda n = \frac{value\ of\ \lambda n\ with\ leaf\ sample}{value\ of\ \lambda n\ without\ leaf\ sample} * 100 \quad (2)$$

Table-3 also includes the SPAD readings on the 15 samples using the SPAD-502. These SPAD values were converted into CCI using Equation 3 [18, 19,20]:

$$CCI_{SPAD} = 1.034 + 0.308(SPAD) + 0.11(SPAD)^2 \quad (3)$$

Table-3. SPAD-502 reading on 12 sample types.

Sample number	Type of leaf	SPAD-502		Measured CCI at different wavelengths				
		Reading	CCI_{SPAD}	680nm	730nm	760nm	810nm	860nm
1	Country Almond tree	36.7	160.49	1.26	7.92	5.11	0.25	0.28
2	Mango tree	44.5	232.56	0.99	10.74	7.05	0.29	0.31
3	Jackfruit tree	63.3	461.28	1.14	31.96	26.15	0.78	0.74
4	Grass	54.9	349.48	1.08	15.02	12.78	0.48	0.51
5	Ficus retusa	42.9	216.69	1.84	66.46	44.28	0.88	0.86
6	Cananga tree	13.6	25.56	0.25	1.66	0.55	0.21	0.15
7	Cassava	59.4	407.44	0.03	24.62	3.09	0.36	0.13
8	Ochna tree	23.7	70.11	0.03	5.07	0.55	0.18	0.72
9	Banana tree	54.5	344.54	0.03	17.57	3.09	0.59	0.18
10	Gooseberry tree	37.4	166.41	0.03	10.34	1.1	0.17	0.06
11	Lime tree	45.5	242.77	0.02	14.58	1.45	0.19	0.06
12	Jackfruit (old leaf)	2.5	2.49	0.12	0.92	0.06	0.55	0.77

Table-4. Device measurement results versus SPAD-502 reading on 15 samples.

Sample number	Type of leaf	Our device			SPAD-502 reading	Absolute Error (%)
		Reading at 730nm	CCI	SPAD equivalent		
1	Country almond tree	7.92	160.44	36.69	36.7	0.03
2	Mango tree	10.74	215.35	42.76	44.5	3.91
3	Jackfruit tree	31.96	466.04	63.63	63.3	0.52
4	Grass	15.02	289.02	49.78	54.9	9.33
5	Ficus retusa	21.28	375.73	47.25	42.9	10.14
6	Cananga tree	1.66	20.43	11.95	13.6	12.13
7	Cassava	24.62	411.79	59.72	59.4	0.54
8	Ochna tree	5.07	99.79	28.59	23.7	20.63
9	Banana tree	17.57	327.35	53.08	54.5	2.60
10	Gooseberry tree	10.34	207.87	41.98	37.4	12.24
11	Lime tree	14.58	281.98	49.16	45.5	8.04
12	Bromelia karatas	21.36	376.68	57.04	58.9	3.16
13	Palm tree	66.31	263.69	47.48	55.0	13.67
14	Plumeria	44.85	478.26	64.48	61.6	4.67
15	Jackfruit tree (old leaf)	0.92	2.23	2.10	2.50	16.00
					Average error (%)	**7.84**

As seen in Table-3, the CCI of our device has the highest values at the wavelength of 730nm therefore the CCIs of this wavelength were used for further investigations in this work. All CCI of 410 points of thdata on each sample over 5 channel CCIs with respected to the red channel are calculated using Equation 1 and an average is taken as the CCI for that channel. Table-3 lists the results.

From the data analysis, it was found that the relationship between the SPAD-502 CCI of Equation 3 and our device CCI in the second-order polynomial is as follows:

$$\mathrm{CCI_{Device}} = -0.3186 * \mathrm{CCI}^2 + 25.418 * \mathrm{CCI} - 20.881 \quad (4)$$

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The CCI_{Device} was then converted into equivalent SPAD numbers for all 15 samples. Table-4 shows the comparison of our results to the SPAD-502 readings. The average error between our device and the SPAD-502 is 7.84%. The worst case is sample #8 (Ochna tree) while the best reading is sample #1 (Country almond tree). Figure-6 shows these two leaves. It can be seen in Table-4 that the old jackfruit leaf in yellow color (sample #15) with very little chlorophyll also has higher error. In general, the results show a better accuracy at the higher levels of chlorophyll in the leaf.

CONCLUSIONS

For the low-cost AD7263 spectrometer using in this work, the wavelength of 730nm is the best to be used for transmission and the 610nm wavelength is good for absorption to measure chlorophyll content index of the leaf and convert into SPAD equivalent. The error of less than 8% is worth for a fraction of the cost of this device which is less than US$100 compared to over US$3000 of a commercial unit. This low-cost device is affordable to the farmers, easy to use in the field, consistent results, not mentioned the capable of IoT and data storage, monitoring, and decision making. Chlorophyll measurements will assist nitrogen management for cost reduction, higher yield, less labor, and precision farming. The device can also be used by plant scientists in the low budget settings. There could be a limitation from this design on the different thickness of the leaf as the light may not be sufficient for the full transmission or the absorption of the different leaves. These are unknown in the interested NIR spectrum. Investigation into the calibration of the device or adaptation to type of the leaf may also be necessary.

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