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Development of an optical sensor for crop leaf chlorophyll content detection

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A B S T R A C T

Nitrogen content in crop leaf is an important indication for evaluating crop health and predicting crop yield. A normalized difference vegetation index (NDVI) is widely used as an indicator in estimating leaf nitrogen content in practice. How to effectively and accurately measure the NDVI value of crop leaves in the field is a challenge on in-field use instrument development. This paper reports the development of a hand-held spectroscopy-based optical sensing device for measuring crop leaf NDVI values under in-field natural light conditions. This optical sensing device could simultaneously measure the spectral reflectance of canopies and the solar intensity at two bands of 610 and 1220 nm, and calculate NDVI value in real-time based on measured spectral reflectance. This device was tested in tomato plants chlorophyll content measurement. A series of field tests were conducted to evaluate the performance of the sensor, and tomato leaf samples were collected for measuring chlorophyll contents as the reference for validation. Obtained results indicated that NDVI values measured with this sensing device had a close correlation with chlorophyll contents of the collected leaf samples measured in laboratory with a UV–vis spectrophotometer ($R^2_{Opt} = 0.66$).

1. Introduction

Crop leaf nitrogen content is an important indicator for assessing growth status and predicting yield and quality of many crops. Previous studies have revealed that nitrogen levels in crop plants could cause spectral reflectance changes on leaves, and leaf chlorophyll content can be served as a measure of plant photosynthesis, nitrogen stress and development stages (Thomas and Oerther, 1972; Blackmer et al., 1994; Cartelat et al., 2005). As deficient nitrogen content will typically cause a low chlorophyll level in leaves, it will result in a reduction in leaf spectral reflectance at the NIR band and an increase in the visible band (Wood et al., 1992; Yoder and Pettigrew-Crosby, 1995; Li et al., 2006). Such a phenomenon makes it possible to assess crop plant nitrogen stress based on measurable leaf spectral reflectance.

Since the 1970s, scientists have conducted extensive researches, including, but not limited to, exploring the feasibility of estimating crop plant nitrogen stress through analyzing canopy spectra features, selecting sensitive wavebands, and formulating spectra-based nitrogen stress estimating models. For example, Walburg et al. (1982) measured spectral reflectance between 0.4 and 2.4 μm wavelength using a spectroradiometer mounted on the boom of a mobile aerial tower. The results showed that crop canopy reflectance spectra had a potential to monitor the growth and development of crops, and the near infrared/red reflectance ratio (0.76–0.90 μm)/(0.63–0.69 pm) differed more between different nitrogen treatments than single band reflectance measures. Tucker (1979) evaluated the relationships between various linear combinations of red and photographic infrared radiances and experimental plot biomass, leaf water content, and chlorophyll content. Regression analysis showed that these linear combinations of the IR/red ratio, the square root of the IR/red ratio, the IR-red difference, the vegetation index, and the transformed vegetation index, could be employed to monitor the photosynthetically active biomass of plant canopies. Xue et al. (2004) reported that a ratio index of reflectance in the NIR band to green band (R_{810}/R_{560}) could represent nitrogen concentration in wheat. After studying the relationship between leaf chlorophyll content and spectral reflectance, Horder et al. (1983) recommended using a "red edge", namely a waveband embracing the maximum slope of leaf reflectance spectra, as an indicator for plant chlorophyll levels. Bell et al. (2004) measured the energy reflected from turf grass canopy at 350–1100 nm wavelengths, found that there existed a close correlation between NDVI and chlorophyll contents ($R^2 = 0.70$), and concluded that NDVI could be used to estimate the chlorophyll content of turf grass.

To make the above findings practically useable devices in-field applications, numerous researches on developing in-field

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use instruments for detecting plant nitrogen content have been reported. For example, Stone et al. (1996) developed an optical sensor for detecting nitrogen content in winter wheat plants. They reported that the device could provide a close correlation between the plant nitrogen content and the Plant Nitrogen Spectral Index (PNSI). Kim et al. (2001) investigated the applicability of using a multispectral camera as an optical sensor for assessing corn plant nitrogen stress, and also found it could provide a reasonable correlation between NDVI and leaf chlorophyll content. Sui et al. (2005) developed a device for detecting nitrogen status in cotton plants by measuring spectral reflectance from canopies in four wavebands of blue, green, red, and NIR with modulated illumination under the sun. Min et al. (2006) used visible and near infrared spectroscopy to estimate nitrogen concentrations in Chinese cabbage. Campbell et al. (2007) used reflectance (R) and fluorescence (F) information to monitor vegetation stress responses. Such crop reflectance could be used as the feedback information to support a variable-rate control for nitrogen applications (Heege and Thiessen, 2002). Noh et al. (2005) used a multispectral image sensor to detect corn plant nitrogen deficiency in real-time for supporting sensor-based variable-rate nitrogen side dressing. In vegetable production, Xu et al. (2006) measured the reflectance of tomato leaves for an early detection of tobacco mosaic virus (TMV-U1) infection, and found that it was possible to distinguish healthy and infected tomato plants based on the reflectance changes in the visible and NIR bands of wavelength.

At present, there are a lot of commercial instruments for detecting the growth and development of crops, but most of them are expensive, mounted on a vehicle or a tower, and used in large-scale applied system or scientific studies. The overall goal of this research was to design a spectra-based, low-cost and hand-held device for in-field use, with the capability of measuring the spectral reflectance of crop leaves and the sunlight intensity at red and NIR bands, and automatically calculating a NDVI valve using the measured raw data for indirectly detecting the nitrogen content in plants. A prototype device, consisting of an optical sensing unit and an electronic control unit, was designed and constructed. This paper reports the validation of using this device in measuring tomato plants. The validation tests were conducted in-field conditions to evaluate the functionality of this prototype, and tomato leaf samples were collected as the reference for measuring chlorophyll contents.

2. Methodology and procedures

2.1. Theoretical design of sensing unit

Traditionally, crop growth is assessed using some indices due to the complicated multi-factor influencing nature. A few vegetation indices have been developed for revealing interested crop growing status information. Among them, a commonly accepted and practically used index is the NDVI (Normalized Difference Vegetation Index), calculated as a ratio differences between measured canopy reflectance in the red and NIR bands (Rouse et al., 1973):

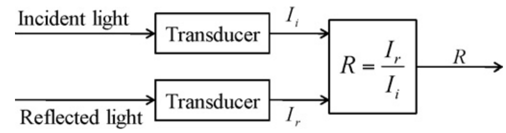

Fig. 1. Illustration of the equation of light reflectance R.

$$\mathrm{NDVI} = \frac{R_{IR} - R_R}{R_{IR} + R_R} \tag{1}$$

This research used NDVI as the indicating parameter due to its capability in providing sensitivity to chlorophyll levels in leafy green vegetation. The developed device used four photoelectricity transducers (two pieces of PDS463-a, Skyray Opto-Electronic Technologies Ltd., Beijing, China; and two pieces of SP-3ML, Kodenshi Korea Corp., Iksan, Korea) to form the sensing core for measuring the light intensity in both red and NIR bands. These optical–electrical transducers convert light intensity into proportional electronic current signal. The light reflectance R can be determined based on the sensed light intensities measured by the sensing core using the following equation:

$$R = \frac{I_r}{I_i} \tag{2}$$

where I_i is the output current signal representing the intensity of the incident light and I_r is the current signal representing the intensity of the reflected light (Fig. 1).

To simplify the signal processing for making the device suitable for in-field use, the current signal was converted into voltage signal. A set of two transducers were then paired to measure crop canopy reflected light and reference sunlight radiation, which was used as an indirect estimation of the incident light to the sensor. The reflectance equation can then be rewritten as follows:

$$R = \frac{K_r U_r}{K_i U_i} = K' \frac{U_r}{U_i} \tag{3}$$

where U_r and U_i are output voltage signals representing the reflected light and the reference sunlight, K_r and U_i are experimentally calibrated constants representing characteristic specifications of the optical unit, and the optical–electrical converters (Fig. 2).

Based on the above relations, the measured reflectance values at NIR band (R_{IR}) and red band (R_R) could be determined using the following equations:

$$R_{IR} = K'_{IR} \frac{U_{rIR}}{U_{iIR}} \tag{4}$$

$$R_R = K'_R \frac{U_{rR}}{U_{iR}} \tag{5}$$

where K'_{IR} and K'_R are experimentally calibrated constants representing components characteristic specifications in NIR and red bands.

The NDVI value could then be calculated using the equation below in terms of measured reflectance in NIR and red bands.

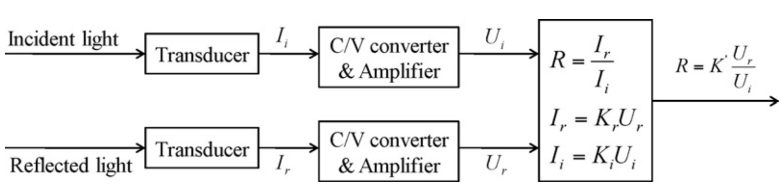

Fig. 2. Illustration of the deduced equation of light reflectance R.

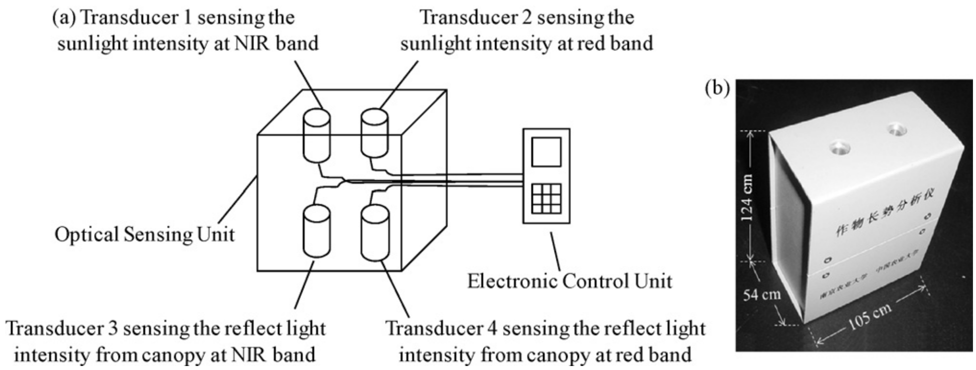

Fig. 3. System schematics of a hand-held optical crop nitrogen content measurement device.

This equation served as the foundation for designing the proposed device crop health in this research.

$$\mathrm{NDVI} = \frac{R_{IR} - R_R}{R_{IR} + R_R} = \frac{K'_{IR} U_{rIR} U_{iR} - K'_R U_{rR} U_{iIR}}{K'_{IR} U_{rIR} U_{iR} + K'_R U_{rR} U_{iIR}} = 1 - \frac{2}{K(U_{rIR} U_{iR} / U_{rR} U_{iIR}) + 1} \quad (6)$$

where U_{rIR} and U_{rR} are the output voltage signals induced by the crop canopy reflected light, U_{iIR} and U_{iR} are the voltage signals induced by the sunlight at NIR and red bands, respectively, and the constant K is the ratio of K'_{IR} over K'_R.

2.2. Physical design of sensing unit

Eq. (6) reveals the theoretical base of instrument design indicating it requires one constant and four variables to estimate a NDVI reading for real-time measurements. Each of the four input variables, U_{rIR}, U_{rR}, U_{iIR} and U_{iR}, requires a separate sensing element to simultaneously measure its corresponding light intensity. The designed optical sensing unit, therefore, consisted of four sensing elements: two for measuring the sunlight intensity and the other two for measuring the crop canopy reflected light. An electronic control unit was designed to control the simultaneous sensing and data recording, and perform real-time NDVI value calculations. As stated in the previous section, the constant K in the governing equation needs to be determined experimentally via calibration tests to represent the characteristic specifications of the composing components.

2.2.1. Optical sensing unit design

To realize the desirable functions, the optical sensing unit uses four transducers to acquire light intensity data (Fig. 3). The dimensions of the optical sensing unit are 105 mm long, 54 mm wide and 124 mm high and the weight is 840 g. Each transducer has a separate optical window for collecting the light, a filter for transmitting the light of a specific wavelength interval, a lens for focusing the light, and an optical–electrical converter for changing optical signals into electrical ones.

The optical windows of two transducers were configured upwards to measure the intensity of the sunlight, and the other two pointed downwards to sense the intensity of the reflected light from the plant canopy. Each pair of the oppositely arranged transducers was equipped with the same type of filters and converters for measuring light intensity under identical conditions. Since NDVI composing with the 1220 nm centered NIR band and 610 nm centered red band showed a good correlation with the variation of nitrogen content of crop plants (Zhu et al., 2007), those two bands were chosen for constructing the optical sensing unit. Specifically, one pair of sunlight and reflected light sensing transducers (transducers 1 and 3) used an InGaAs photodiode, sensitive to a light spectrum between 1000 and 1650 nm at a light active area of 1.5 mm × 1.5 mm, were used as the transducers for acquiring NIR band data. A 1220 ± 6 nm filter of 20 mm diameter was installed in front of the transducer sensing only the light within the interested band. Similarly, a 610 ± 6 nm filter of 20 mm diameter was used in transducers 2 and 4 (the red band sensing pair) to transmit the light of desired band to a silicon photocell transducer, sensitive to a light spectrum between 400 and 1100 nm with a light active area of 5 mm × 5 mm, for acquiring red band data. To reduce the influence of the solar elevation angle on light intensity, a milky diffuse glass was used as the optical window for the two up-view channels. To capture reflected light from the object of interest, the down-looking transducers were designed with 30° field of view (Fig. 4). With a 20 mm diameter of optical window (d_1), this field of view would result in an adjustable detectable area, S_c, depending on the distance of the optical windows above the crop canopy (h) as follows:

$$S_c = \pi\left(\frac{d_2}{2}\right)^2 = \pi(h \tan 15^\circ)^2 \quad (7)$$

where d_2 is the diameter of the detectable area.

For example, supposing that the optical unit was put at the height of 1 m, according to Eq. (7), the detectable area (S_c) equals to 0.23 m^2.

2.2.2. Electronic control unit design

The electronic control unit was designed to control the data acquisition process and convert the light-induced electric current signals to NDVI value. As illustrated in Fig. 5, this unit used a current/voltage (C/V) converting chip to transform electric current

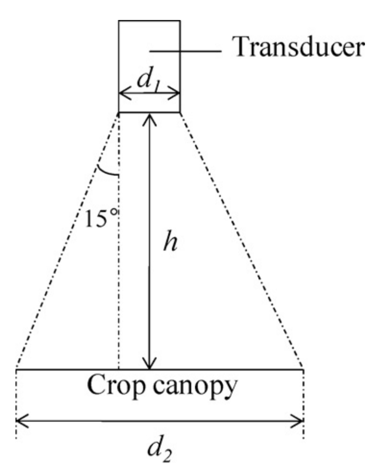

Fig. 4. Illustration of the sensible area of down-looking transducers.

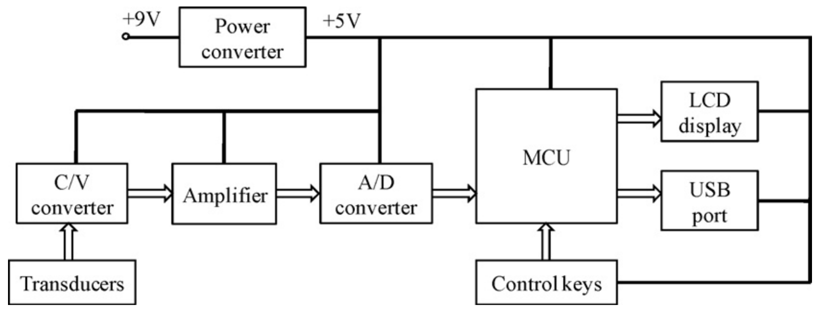

Fig. 5. System schematics of the electronic control unit.

signals into voltage signals, an amplifier to fit voltage signals in a range of 0–5 V, and an A/D converter to transfer the output of analog signals into digital signals. A microprocessor was used to control the simultaneous measuring process of four transducers, calculate NDVI values in real-time, and display results on a LCD monitor.

Designed for manual operation, this device used three keys of "Reset", "Measure" and "Store" to send commands to the microprocessor for controlling the sensing process. In a typical operation, the user firstly needs to press the "Measure" key to read the voltage signals from four transducers. The NDVI will be calculated automatically in terms of the read-in voltage signals from those transducers, and displayed on the LCD monitor. It takes 100 ms to output an NDVI value. If the user needs to save the data, the "Store" key has to be pressed to record the calculated NDVI values in a Flash Disk via a USB port.

The whole circuit was powered by two +9 V 1200 mAh Li batteries. Due to the power requirement of other chips, the voltage in the circuit was changed from +9 V into +5 V by using a power converter.

2.2.3. Software design

An embedded software program, written in C language and implemented in the electronic control unit, was designed to manage two basic functions of acquiring signals from all four sensing elements and storing acquired signals in a retrievable way. To support those functions, the software was composed of two interruptive subprograms of measurement and data storage as illustrated in Fig. 6.

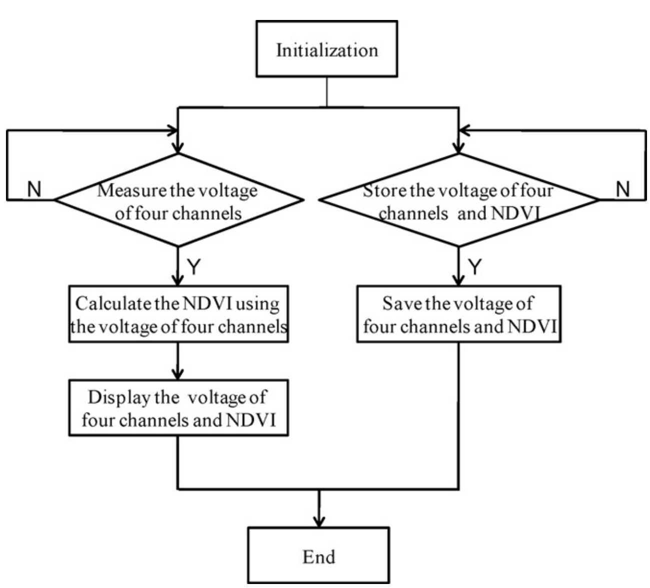

Fig. 6. Flow chart of the embedded data management program.

In implementation, the program is always at a waiting status after the system is initialized. The device switches to the data acquisition mode after the "Measure" key is pressed. Under this mode, the program implements the measurement subprogram to read the sensor output voltage from each transducer for ten times and output an average value as the measurement outcome. The device executes the storing function to save the obtained data in a Flash Disk only after the "Store" key has been pressed.

2.3. System calibration

After the prototype of instrument was fabricated, a calibration test was conducted for experimentally determining the constant K in the governing equation using a white reference panel with approximately 100% reflectance across the entire spectrum. The panel was made of Spectralon, a proprietary material made of cintered polytetrafloraethylene (Analytical Spectral Device Inc., Boulder, Colorado). The calibration tests were carried out outdoors between 11:00 and 14:00 on sunny days to minimize the influence of light intensity on the measurement process. In the test, the prototype was perpendicularly placed 10 cm above the panel, and the output signals from all four channels were collected at 20 min intervals. Each measurement was repeated five times and the average value was recorded as the final result of the measurement. As mentioned above, the reflectance of the white reference panel is 100% across the entire spectrum, which means that $R_{IR} = R_R = 100\%$, and consequently Eq. (6) equals 0. The equation for calculating K was deduced as follows, denoting by the recorded data from the calibration test:

$$K = \frac{U_{rR} U_{iIR}}{U_{rIR} U_{iR}} \quad (8)$$

where U_{rIR} and U_{rR} are the recorded voltage signals corresponding to the 100% reflectance in NIR band and red band, U_{iIR} and U_{iR} are the voltage signals induced by the radiation of sunlight in NIR band and red band.

The results showed that K values from the calibration process ranged from 0.92 to 1.06, with a mean value and standard deviation of 1.00 and 0.04, respectively.

3. Field validation tests and result analysis

A series of field tests was conducted to verify the performance of the developed device in detecting NDVI of tomato plants. A portable FieldSpec^{TM} Spectroradiometer (Analytical Spectral Device Inc., Boulder, Colorado), with a sensible range from 325 to 1075 nm at a 1 nm sampling interval and an UV–vis spectrophotometer (SP-2102, Shanghai Spectrum Instruments Co., Ltd., Shanghai, China) were used to measure the reflectance spectrum and the chlorophyll contents of the same plant sample, respectively, as the reference for quantitatively assessing the performance of the device.

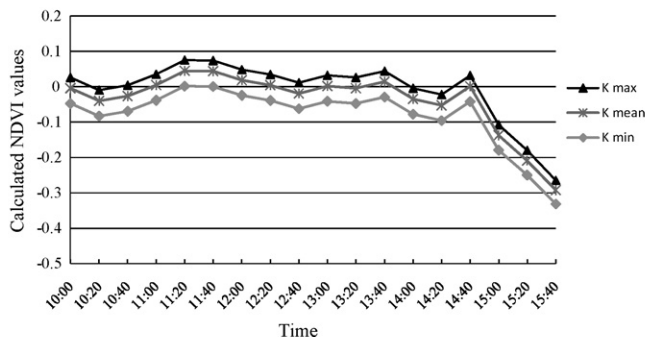

Fig. 7. Calculated NDVI values of the white reference panel at different time over 1 day using the maximum value, the mean value and the minimum value of K. The unrealistic low NDVI values after 14:40 was caused by the reduced incident sunlight to the reference channel due to the low solar angle.

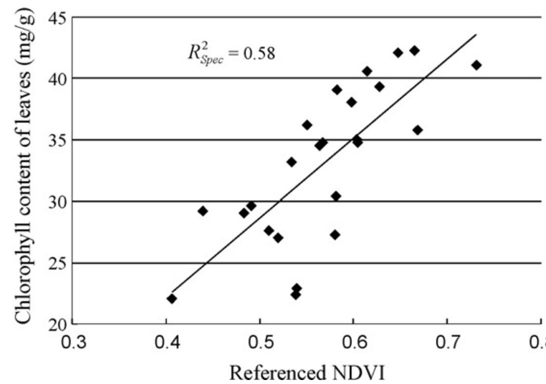

Fig. 8. The correlation between the chlorophyll content and the referenced NDVI calculated by the reflectance measured by FieldSpec™ Spectroradiometer at 703 and 782 nm bands.

3.1. K determination and repeatability analysis

In order to choose a suitable K value and check the repeatability of the device, a simulated field validation test was conducted to measure NDVI values of the same white reference panel. Voltage values of U_{rIR}, U_{rR}, U_{iIR} and U_{iR} were recorded for calculating the NDVI value of the white reference panel. Then, the NDVI values of the white panel using the maximum value, the mean value and the minimum value of K were calculate, according to Eq. (6). A threshold value of 0.1 for the standard deviations (σ) of measured NDVI values was set as the acceptable performance level in detecting crop nitrogen stress for field application. To simulate actual field measurement conditions, the validation test was carried out in a sunny day with frequent clouds in the sky during the testing period. In this validation test, the data was collected at 20 min intervals between 10:00 and 15:40, under natural light. Each measurement was repeated three times and the average value was taken as the measured data. Similar to the calibration test, the sensing unit was perpendicularly positioned to the panel at 10 cm above the reference panels in the validation test. As shown in Fig. 7, the NDVI values using the maximum and minimum values of K were all far from the theoretical value 0, but by contrast, the calculated results using the mean value of K was closely distributed within a small range around 0 from 10:00 to 14:40. The mean value was approximately 0 near the theoretical value, and the standard deviation (σ) was 0.028 for this period, which satisfied the design requirement of σ value less than 0.1. Based on the above results, the governing equation for a real-time NDVI measurement was represented as follows:

$$\mathrm{NDVI} = 1 - \frac{2}{1.00 \times (U_{rIR}U_{iR}/U_{rR}U_{iIR}) + 1} \tag{9}$$

Fig. 7 also shows a rapid fall in the measured NDVI values after 14:40, which was mainly attributed to a reduction in incident sunlight into the reference channel due to the large change of the solar angle surpassed the diffusive optical window could compensate for. Through visual observation, the solar angle was noticeably lower after 14:40 during the test day. The results included that the current design could support the developed device to work properly when the solar angle was above a threshold value.

Such performance deterioration after the solar angle was below a threshold level indicated that to furnish the developed device with reasonably repeatability in canopy reflectance measurement over entire daylight period, a solar angle compensation mechanism was necessary for ensuring sufficient sunlight exposure at the reference channels.

3.2. Field test and results analysis

After K value was chosen and performance repeatability was analyzed, the prototype device was also tested in a series of field tests to evaluate its practical performance in measuring tomato plant nitrogen stress in a greenhouse environment under natural light. In this evaluation test, leaves of tomato plants were measured using both the prototype device and the FieldSpec™ Spectroradiometer. Both instruments were placed vertically about 10 cm above the plants during the test. A total of 24 samples were measured in this test. After each instrument measurement, leaf samples from testing plants were collected for measuring chlorophyll content in the laboratory. To do so, 0.4 g leaf sample was filled in test tubes with 25 ml solution mixed acetone and ethanol in a 2:1 ratio. After placing the tubes in a dark room for 24 h to dissolve the chlorophyll in the solution, the chlorophyll contents of those processed samples were measured using an UV–vis spectrophotometer.

Define R^2_{Opt} be the correlation coefficient between the NDVI values read from the prototype optical device and the chlorophyll contents measured using the UV–vis spectrophotometer, and R^2_{Spec} be the correlation coefficient between the referencing NDVI, determined by the FieldSpec™ Spectroradiometer measured reflectance and the chlorophyll content. Due to the limited wavelength range of the reference instrument between 325 and 1075 nm, the reflectance at 1220 nm could not be obtained from the FieldSpec™ Spectroradiometer. For this reason, R^2_{Spec} and R^2_{Opt} could not be compared using the same wavelengths. All possible combinations of two wavelengths, one chosen from the red band (600–710 nm) and the other from the NIR band (760–1075 nm), were evaluated by calculating R^2_{Spec}. The results showed that the

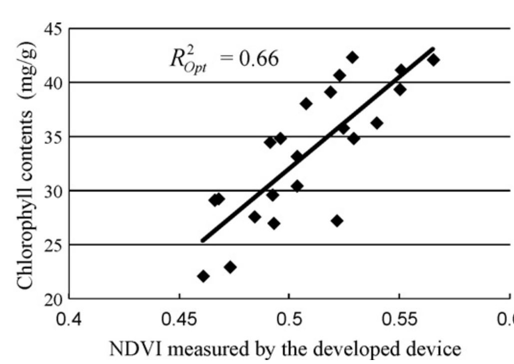

Fig. 9. Correlation between the chlorophyll contents measured using the UV–vis spectrophotometer and the NDVI values read from the developed optical device.

values of R^2_{Spec} ranged from 0.35 to 0.58, with the maximum came from the combination of 703 and 782 nm wavelengths. Figs. 8 and 9 show the distribution and regression results of the maximum R^2_{Spec} and R^2_{Opt} in terms of the measured NDVI values for evaluating the performance of the prototype device. As the R^2_{Opt} value (0.66) was higher than the maximum value of R^2_{Spec} (0.58), it indicates that the developed optical device provides a better accuracy in NDVI value determination than the referencing instrument under the test condition. Such a better performance could be attributed to the capability of the developed optical device in compensating for incident light changes using a sunlight measurement channel.

4. Conclusion

This paper reports the development procedures of a low-cost hand-held multispectral nitrogen stress sensing device. This device was evaluated by measuring nitrogen stress in tomato plants. The results obtained from field tests indicate that the developed optical device meets the design requirement ($\sigma < 0.1$) for field data collection. Both laboratory and field tests showed that this developed device could detect the nitrogen content level of tomato plants. A higher correlation coefficient was found between detected NDVI values of crop canopy and measured chlorophyll contents in plant leaves when using the developed device ($R^2_{Opt} = 0.66$) than the widely used FieldSpec^{TM} Spectroradiometer (the maximum of R^2_{Spec} equals to 0.58). Such a higher correlation implied a better accuracy in nitrogen stress detection. More field tests are necessary to verify the applicability of the developed device to other crops before it can reliably be used for actual field data collection.

Acknowledgements

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