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Evaluation of a Plant Quality Monitoring System Based on Visible and Near-Infrared Spectroscopy Sensors in a Controlled Environment

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Abstract: The increasing demand for agricultural production requires reliable and non-destructive methods for monitoring plant physiological conditions in real time, particularly in controlled environments. Spectral sensing in the visible to near-infrared (VIS–NIR) region offers a promising approach; however, the performance of low-cost sensors is often limited by calibration accuracy, wavelength-dependent sensitivity, and insufficient validation against plant physiological indicators. This study aims to evaluate the performance of a VIS–NIR plant monitoring system based on the AS7265x multispectral sensor in a controlled hydroponic environment. Lettuce (Lactuca sativa L.) was grown under two nutrient concentrations (600 ppm and 1200 ppm), and spectral reflectance data were collected across the 410–760 nm range. Sensor measurements were calibrated and validated against a LI-COR LI-180 reference spectrometer using linear regression, with performance assessed using the coefficient of determination (R^2), root mean square error (RMSE), and spectral response consistency. The results show strong calibration performance, with wavelength-specific R^2 values ranging from 0.9682 to 0.9870 and RMSE values between 0.26965 and 5.19772. Although a systematic offset was observed, the AS7265x sensor preserved key spectral patterns, particularly in the green (510–560 nm) and red-edge (705–730 nm) regions. Differences in nutrient concentration were consistently reflected in both spectral responses and SPAD measurements, indicating sensitivity to plant physiological variations. These findings demonstrate that the AS7265x sensor provides reliable spectral information for relative plant monitoring and has strong potential as a cost-effective tool for plant quality assessment in controlled environments.

Keywords: AS7265x sensor, VIS–NIR spectroscopy, Spectral reflectance, Plant monitoring

Introduction

Climate change and rapid population growth have significantly increased pressure on global agricultural systems, with food demand projected to rise alongside a global population reaching 9.7 billion by 2050 (Zhao et al., 2024). This situation intensifies the need for sustainable agricultural practices while minimizing environmental impacts caused by limited land and water resources (Sanyaolu & Sadowski, 2024). In response, precision agriculture has been developed to improve productivity and resource efficiency through data-driven management. A critical requirement within this approach is the ability to monitor plant physiological conditions accurately and continuously throughout the growth cycle.

Conventional plant quality assessment methods, such as laboratory-based biochemical analysis, are destructive, time-consuming, and costly. These limitations prevent their application for continuous and real-time monitoring, particularly in dynamic cultivation systems. As a result, they are not suitable for tracking plant responses during growth stages. Non-destructive sensing technologies are therefore required to enable continuous observation of plant conditions and to support timely decision-making in modern agricultural systems.

Controlled Environment Agriculture (CEA), including hydroponic systems and plant factories, has emerged as an effective strategy to reduce environmental variability and ensure stable crop production (Engler & Krarti, 2021). These systems enable precise regulation of environmental factors such as light, temperature, humidity, and nutrient supply, which enhances plant growth performance (Dsouza et al., 2023; Villagran et al., 2025). However, monitoring in CEA is still largely focused on environmental parameters rather than direct plant responses. This creates a limitation in understanding how plants physiologically respond to controlled conditions.

Advancements in plant phenotyping have introduced various sensor-based approaches to assess plant condition in a non-destructive manner (Jung & Arar, 2023). Several studies have integrated sensing technologies with computational methods to improve monitoring capabilities (Lolitasya et al., 2025; Dey & Ahmed, 2025). Despite these developments, existing systems often face challenges related to measurement instability, sensitivity to environmental variations, and high implementation costs (Bai et al., 2025). These constraints limit the practical application of such systems, particularly in controlled agricultural environments.

Spectroscopic techniques in the visible to near-infrared (VIS–NIR) region provide a promising solution for non-destructive plant monitoring. Reflectance signals in this spectral range are closely associated with plant physiological properties, including chlorophyll content, leaf structure, and nutrient status (Lazim et al., 2023). Specific wavelength regions, such as the green band (approximately 510–560 nm) and the red-edge region (approximately 705–730 nm), are highly sensitive to variations in chlorophyll concentration. These spectral characteristics have been widely utilized for assessing plant condition in agricultural applications (Atanassova et al., 2025).

Recent studies have explored the application of low-cost multispectral sensors, such as the AS7265x, for plant monitoring. Lopin et al. (2025) demonstrated the capability of the AS7265X sensor for non-destructive chlorophyll estimation based on spectral reflectance. However, previous systems were often limited to indirect measurements, such as photosynthetic photon flux density (PPFD), without direct validation against plant physiological parameters. This limitation reduces the interpretability of spectral data and constrains its use for plant quality assessment.

In addition, the performance of low-cost spectral sensors is often affected by calibration accuracy, wavelength-dependent sensitivity, and systematic bias relative to reference spectrometers. Without proper calibration, these sensors may produce inconsistent reflectance values across wavelengths. Furthermore, the relationship between spectral reflectance and physiological indicators, such as chlorophyll content, is not always explicitly validated. This condition limits the reliability of these systems for practical applications in precision agriculture.

The objective of this study is to evaluate the performance of a VIS–NIR plant monitoring system based on the AS7265x sensor in a controlled hydroponic environment by assessing its calibration accuracy, spectral response consistency, and its relationship with plant physiological status. The evaluation is conducted through comparison with a reference spectrometer and validation using SPAD measurements as an indicator of chlorophyll content. This approach ensures that both the technical performance of the sensor and its physiological relevance are systematically examined. The results of this study provide a structured evaluation of low-cost multispectral sensing for plant monitoring and contribute to improving the reliability of spectral measurements. The findings also support the application of VIS–NIR sensors for relative assessment of plant quality in controlled environments.

Method

Data Collection

This study was conducted at the Smart Agriculture Research Center, Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada. The monitoring system was implemented in a controlled environment using a SmartAgri growth chamber, where environmental variables such as temperature, humidity, light intensity, and nutrient supply were regulated. The overall experimental workflow, including calibration, data acquisition, validation, and evaluation processes, is illustrated in Figure 1.

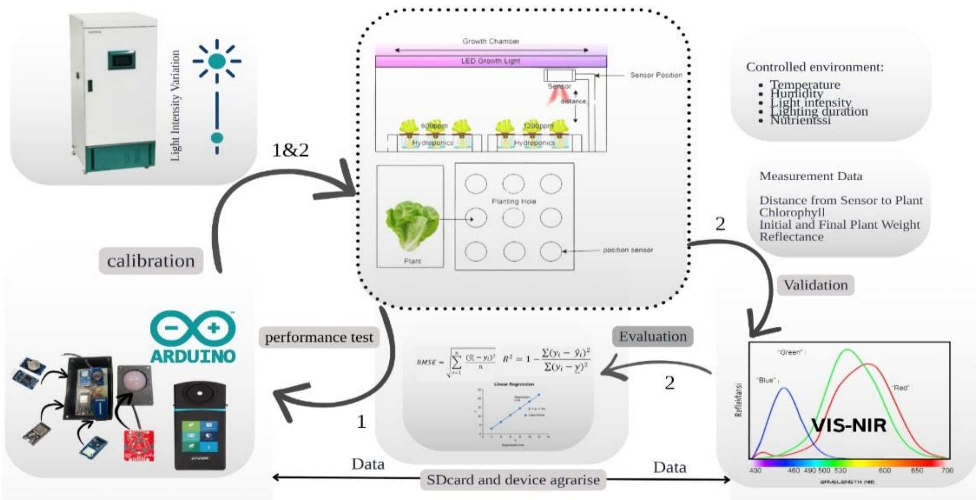

Figure 1. Conceptual framework of the VIS–NIR-based plant monitoring system, including calibration, acquisition, validation, and evaluation processes

The system integrates a VIS–NIR multispectral sensor (AS7265x), a LI-COR LI-180 reference spectrometer, and a microcontroller-based data acquisition unit. As shown in Figure 1, the calibration stage was performed using the reference spectrometer to establish a relationship between sensor output and standard spectral measurements. Data acquisition was conducted using lettuce plants at 28 days after transplanting, with reflectance values collected across intensity levels ranging from 10% to 100% at 5% increments to ensure sufficient calibration coverage.

The data acquisition algorithm and system operation flow are presented in Figure 2. The system was configured to automatically record spectral data within the 410–760 nm range at regular intervals. When connected to a network, data were transmitted to a cloud-based platform, while offline data were stored locally on a microSD card.

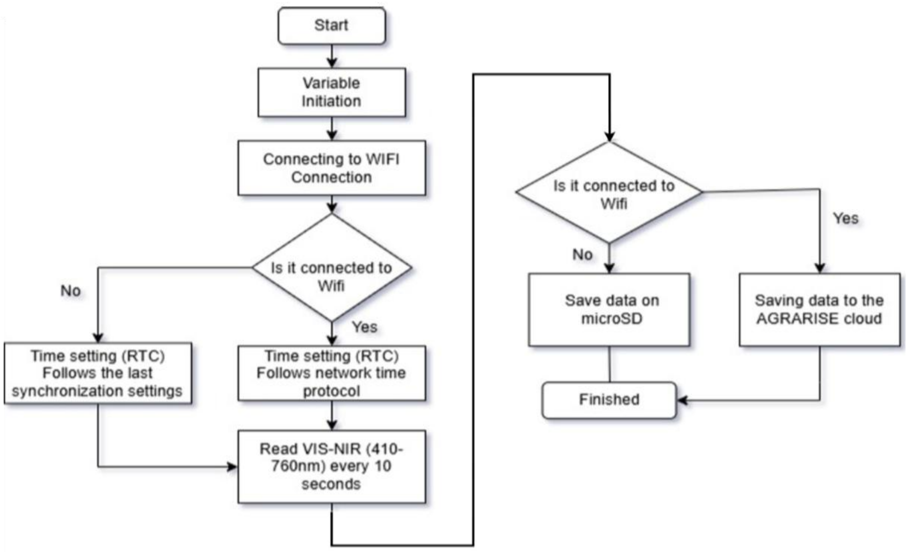

Figure 2. Flowchart of the VIS–NIR data acquisition and transmission algorithm

Model Evaluation

Linear regression analysis was applied to quantify the relationship between the AS7265x sensor measurements and the LI-COR LI-180 reference data. In this model, spectral reflectance obtained from the AS7265x sensor was defined as the dependent variable, while the reference measurements were treated as the independent variable. This approach enables the development of calibration equations to reduce systematic differences between sensors

The performance of the regression model was evaluated using the coefficient of determination (R^2), as defined in Equation (1). This metric represents the proportion of variance in the reference data that can be explained by the calibrated sensor output. Higher R^2 values indicate stronger agreement between the sensor and the reference instrument.

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \tag{1}$$

where $\hat{y}_i$ is the predicted value from the AS7265x sensor, y_i is the corresponding LI-COR LI-180 measurement, and $\bar{y}$is the mean of the reference data.

The root mean square error (RMSE) was used to quantify the average deviation between predicted and reference values. RMSE provides an absolute measure of prediction error and complements R^2 in evaluating model performance (Chicco et al., 2021). The RMSE is calculated as shown in Equation (2).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \tag{2}$$

where n represents the number of observations. In this study, R^2 and RMSE were jointly used to assess calibration accuracy and predictive reliability across wavelengths.

System Implementation

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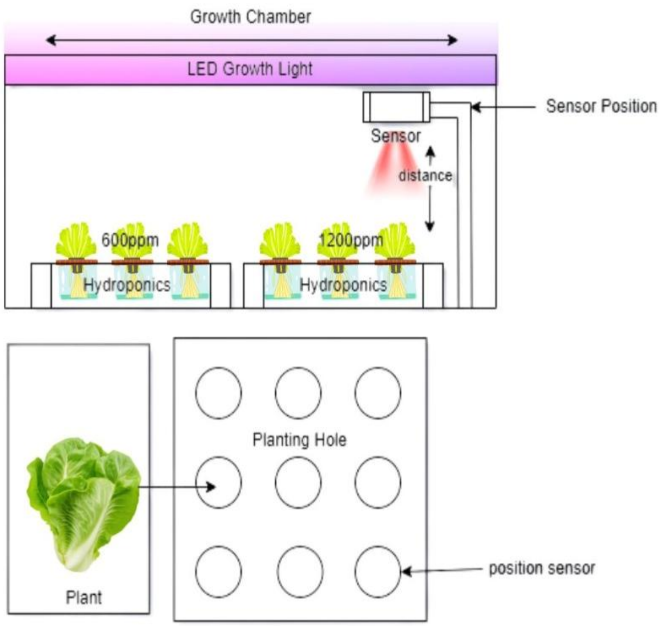

Figure 3. Experimental setup of the monitoring system in a controlled hydroponic environment, including sensor placement and nutrient treatments

The monitoring system was implemented in a controlled hydroponic cultivation setup using lettuce (Lactuca sativa L.) as the experimental plant. The spatial arrangement of the growth chamber, sensor position, and hydroponic system is presented in Figure 3. The sensor was positioned above the plant canopy to capture reflectance signals consistently across all samples.

Lettuce plants at 28 days after planting were observed over a 10-day period, with measurements conducted on day 1, day 5, and day 10. Each measurement consisted of three replications and was performed at three time points (08:00, 14:00, and 18:00 WIB) to minimize temporal variability. The recorded spectral values were averaged to obtain representative reflectance data for each condition.

Two nutrient treatments were applied to evaluate system performance under different plant physiological conditions, namely 600 ppm (pH 5.5–6.5) and 1200 ppm (pH < 5). Plants were grown under controlled environmental conditions, including a constant temperature of 20°C, relative humidity of 80%, and LED lighting operated from 06:00 to 24:00 at 50% intensity. The distance between the sensor and the plant canopy was maintained at 10 cm to ensure consistent measurement geometry. Chlorophyll content was measured using a SPAD meter to provide independent physiological validation.

Spectral Acquisition and Reflectance Conversion

Spectral data were acquired using the AS7265x sensor within the wavelength range of 410–760 nm. The sensor recorded raw spectral responses as digital intensity values corresponding to reflected light at each wavelength. These raw values were subsequently converted into relative reflectance to improve comparability across samples and measurement conditions.

Reflectance values were calculated using white and dark reference calibration, as defined in Equation (3). This approach corrects for sensor dark current and reduces the influence of ambient light variability during measurement. The resulting reflectance values provide a normalized representation of plant spectral response.

$$R(\lambda) = \frac{I_{sample}(\lambda) - I_{dark}(\lambda)}{I_{white}(\lambda) - I_{dark}(\lambda)} \quad (3)$$

where $I_{sample}(\lambda)$is the intensity measured from the plant sample, $I_{white}(\lambda)$is the intensity from a white reference surface, and $I_{dark}(\lambda)$is the dark reference intensity. This calibration procedure improves the consistency and reliability of spectral measurements across different acquisition sessions.

Results and Discussion

Sensor Calibration Performance

Table. 1 Linear regression models for reflectance calibration between the AS7265x sensor and the LI-COR LI-180 reference spectrometer

Wavelength (nm)	Linear regression model (y = ax + b)	R^2	RMSE
410	0.8342x – 0.0261	0.9870	0.26965
435	0.8210x – 0.8529	0.9713	1.63401
460	0.8108x – 1.5833	0.9682	2.66863
485	0.8855x – 0.5089	0.9701	2.23594
510	0.8614x – 0.9129	0.9679	3.60679
535	0.8905x + 0.0541	0.9688	5.19772
560	1.5450x + 8.3770	0.9755	4.94921
585	1.2220x + 3.6279	0.9686	3.50987
610	0.8899x + 0.3516	0.9695	3.08239
645	0.9579x + 1.1286	0.9706	2.54638
680	0.8320x + 0.1092	0.9757	1.35128
705	1.0785x + 1.3877	0.9751	1.99535
730	1.0273x + 1.3788	0.9742	2.25126
760	1.0963x + 0.6775	0.9825	0.97584

Linear regression analysis was conducted to quantify the calibration relationship between the AS7265x sensor and the LI-COR LI-180 reference spectrometer across individual wavelengths within the 410–760 nm spectral range. This approach establishes a functional relationship between sensor output and reference measurements, allowing systematic deviations to be corrected. The resulting calibration models form the basis for evaluating the reliability of the sensor under controlled experimental conditions (Chen & Chen, 2022).

As presented in Table 1, the calibration models exhibit consistently high coefficients of determination (R^2), ranging from 0.9682 to 0.9870 across all wavelengths. These results indicate a strong linear relationship between the AS7265x sensor and the LI-COR LI-180 reference measurements. The consistency of R^2 values across the spectral range suggests that the sensor is capable of capturing reflectance trends with high stability after calibration.

The highest calibration performance is observed at 410 nm and 760 nm, where high R^2 values coincide with relatively low RMSE values. This combination indicates strong agreement and low prediction error at both ends of the spectral range. In contrast, higher RMSE values are observed in the 510–560 nm region, as shown in Table 1, indicating reduced calibration accuracy within the green spectral band.

The increased residual error in the green region is likely associated with the sensitivity of leaf reflectance to physiological variability, particularly chlorophyll concentration and internal leaf structure. Variations in these properties can amplify discrepancies between sensor measurements, especially when using discrete multispectral sensors. In addition, differences in sensor spectral response at specific wavelengths may contribute to the observed deviations.

The regression coefficients further indicate that most slope values are close to unity, reflecting proportional agreement between the AS7265x sensor and the reference instrument. However, deviations from unity are evident at certain wavelengths, such as 560 nm, where the slope exceeds 1.5, indicating wavelength-dependent sensitivity differences. The presence of non-zero intercept values across several wavelengths also confirms the existence of systematic bias, although its magnitude remains relatively limited.

These results demonstrate that the AS7265x sensor provides consistent reflectance measurements after calibration, with performance varying depending on wavelength. The calibration models presented in Table 1 enable the correction of systematic differences and support the use of the sensor for relative spectral analysis in controlled environment applications.

Spectral Response Consistency Between Sensors

The spectral response comparison between the AS7265x sensor and the LI-COR LI-180 reference spectrometer is presented in Figure 4. Both instruments exhibit highly consistent reflectance patterns across the 410–760 nm wavelength range for both nutrient treatments. Characteristic spectral features are clearly observed, including reflectance peaks in the green region (approximately 510–560 nm) and a subsequent decline toward the red region, followed by a slight increase in the red-edge region.

Despite the similarity in spectral shape, the AS7265x sensor consistently produces higher reflectance values than the LI-COR LI-180, particularly within the 435–610 nm range, as shown in Figure 4. This indicates the presence of a systematic offset between the two instruments, which is consistent with the non-zero intercept values obtained from the calibration models. The magnitude of this deviation appears more pronounced under the 600 ppm treatment, suggesting that plant condition may influence the degree of measurement bias between sensors.

The consistency in spectral shape between the two sensors indicates that the AS7265x is capable of capturing relative spectral variations reliably. This is a critical aspect for plant monitoring applications, where the interpretation of spectral patterns is often more relevant than absolute reflectance values. The ability to reproduce similar spectral curves under different treatments demonstrates that the sensor maintains stability in detecting changes in plant optical responses.

As illustrated in Figure 4, distinct differences between the 600 ppm and 1200 ppm treatments are observed, particularly in the green and red-edge regions. These differences are associated with variations in chlorophyll content and leaf structure, which directly affect light absorption and scattering properties. Higher reflectance values under the 1200 ppm treatment indicate improved physiological conditions, likely due to enhanced nutrient availability.

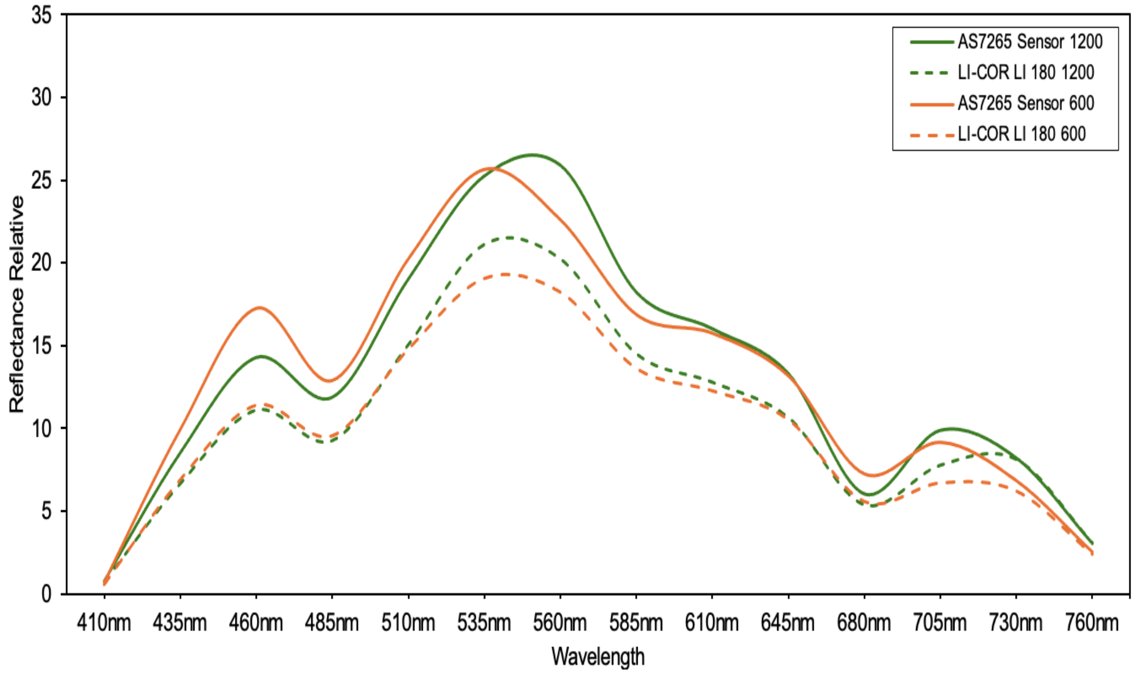

Figure 4. Spectral response comparison between the AS7265x sensor and the LI-COR LI-180 under different nutrient concentrations (600 ppm and 1200 ppm)

The spectral behavior in the red-edge region (approximately 705–730 nm) further supports this interpretation, as this region is highly sensitive to changes in chlorophyll concentration and plant vigor. A shift or enhancement in reflectance within this region is commonly associated with improved plant physiological status. The ability of the AS7265x sensor to capture these variations indicates that it can detect physiologically relevant changes in a non-destructive manner (Ali et al., 2022). These results demonstrate that, although a systematic offset exists, the AS7265x sensor preserves the spectral characteristics observed by the reference instrument. This capability enables its application for relative plant monitoring and comparative analysis under controlled environmental conditions (Sutherland et al., 2024).

System Evaluation Under Different Nutrient Conditions

To evaluate the performance of the monitoring system under different plant conditions, regression analysis was conducted for two nutrient treatments (600 ppm and 1200 ppm). The spectral reflectance curves obtained from both sensors show consistent patterns across all measured wavelengths, indicating that the system is able to capture similar spectral responses under varying nutrient conditions. In addition, the relationship between the AS7265x sensor and the LI-COR LI-180 was examined using linear regression to assess measurement agreement.

The spectral reflectance comparison and regression results are presented in Figure 5. The reflectance curves in Figure 5(a) and 5(c) demonstrate similar spectral shapes between the two instruments, particularly in the green and red-edge regions. Furthermore, the scatter plots in Figure 5(b) and 5(d) indicate a strong linear relationship, confirming that the sensor is capable of tracking the reference measurements under both nutrient treatments.

As presented in Table 2, high coefficients of determination (R^2) were obtained for both treatments, with values of 0.9819 for 600 ppm and 0.9915 for 1200 ppm. These results indicate that the AS7265x sensor maintains a strong linear relationship with the reference instrument under varying nutrient conditions. The slightly higher R^2 observed at 1200 ppm suggests more stable spectral behavior under improved physiological conditions.

The regression coefficients further reveal that the slope values remain below unity for both treatments, indicating that the AS7265x sensor tends to underestimate reflectance magnitude relative to the LI-COR LI-180. At the same time, the positive intercept values indicate the presence of a systematic offset between the two instruments. This behavior is consistent with the deviation from the ideal 1:1 relationship observed in Figure 5(b) and 5(d).

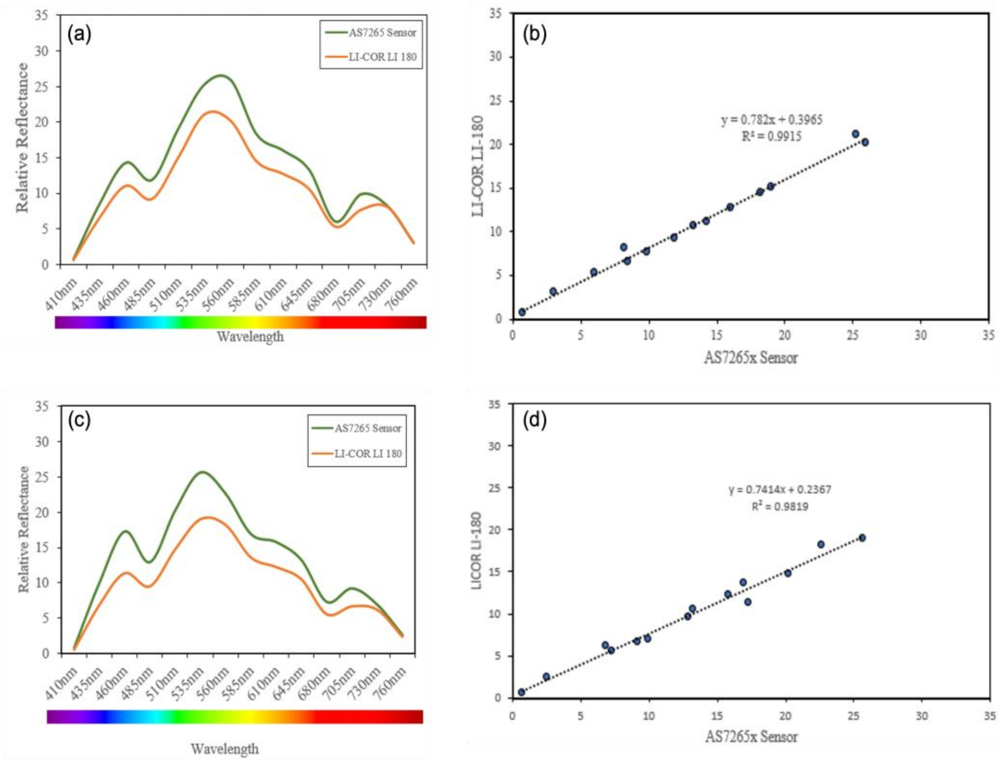

Figure 5. Spectral reflectance and regression analysis under different nutrient concentrations: (a) spectral reflectance at 1200 ppm, (b) regression at 1200 ppm, (c) spectral reflectance at 600 ppm, and (d) regression at 600 ppm across key wavelength regions (435–485 nm, 510–560 nm, and 705–730 nm)

Table 2. Linear regression performance of the AS7265x sensor under different nutrient concentrations

Plant Nutrition	Slope (a)	Intercept (b)	R²	RMSE
600 ppm	0.7414	0.2367	0.9819	11.17
1200 ppm	0.7820	0.3965	0.9915	11.56

The RMSE values presented in Table 2 are higher compared to the wavelength-specific calibration results, indicating increased prediction error when multiple wavelengths are evaluated simultaneously. This effect is likely caused by cumulative variability across spectral bands, combined with physiological changes in plant samples during the observation period. Factors such as leaf structure, water content, and chlorophyll concentration contribute to this variability. Despite these deviations, both sensors consistently capture key spectral regions associated with plant physiological responses, as shown in Figure 5(a) and 5(c). Prominent features are observed in the blue (460–485 nm), green (510–560 nm), and red-edge (705–730 nm) regions, which are closely related to chlorophyll absorption and leaf structural properties. This consistency indicates that the sensor is capable of detecting meaningful variations in plant condition under different nutrient treatments.

The results demonstrate that the AS7265x sensor is able to follow the spectral response pattern of the reference instrument under varying nutrient conditions, although absolute agreement is not fully achieved. The presence of systematic bias and increased error at aggregated levels highlights the importance of calibration for quantitative applications. The preserved spectral pattern, however, supports its use for relative plant monitoring in controlled environments.

Effect of Nutrient Concentration on Spectral Characteristics

Variations in nutrient concentration resulted in observable differences in plant physiological response, as reflected by SPAD measurements. Plants grown under higher nutrient availability exhibited increased chlorophyll content compared to those under lower nutrient conditions. This difference indicates that nutrient supply directly influences plant physiological status through chlorophyll accumulation. The comparison of average SPAD values under different nutrient concentrations is presented in Figure 6. As shown in the figure, plants grown under 1200 ppm exhibit higher SPAD values than those grown under 600 ppm. This pattern confirms that increased nutrient concentration enhances chlorophyll content, which is a key indicator of plant health and photosynthetic capacity.

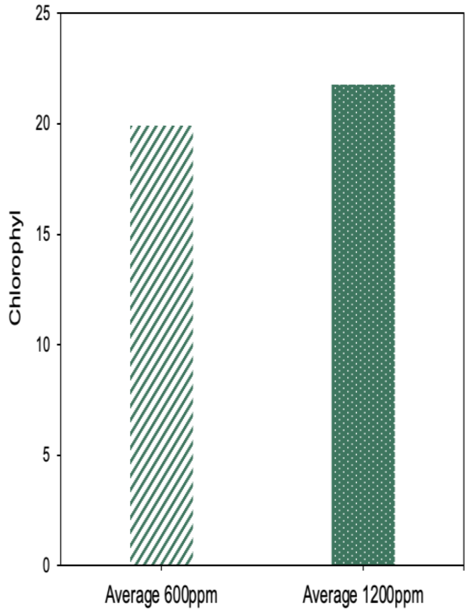

Figure 6. Comparison of average SPAD values under different nutrient concentrations (600 ppm and 1200 ppm), indicating differences in leaf chlorophyll content

The variation in SPAD values is consistent with the spectral reflectance patterns observed in the previous section, particularly in the green (510–560 nm) and red-edge (705–730 nm) regions. These spectral regions are highly sensitive to chlorophyll concentration and nitrogen status, as chlorophyll strongly affects light absorption and internal scattering within leaf tissues. The agreement between SPAD measurements and spectral responses indicates that nutrient-induced changes are reflected in both physiological and optical plant characteristics. Higher nutrient availability promotes chlorophyll synthesis, which increases light absorption in the blue and red regions while modifying reflectance behavior in the green region. In addition, changes in leaf internal structure, including increased cell density and enhanced scattering, influence reflectance in the red-edge region. These combined effects explain the stronger spectral responses observed under the 1200 ppm treatment.

The improved agreement between the AS7265x sensor and the reference instrument under higher nutrient conditions, as discussed in the previous section, suggests that plant physiological stability contributes to more consistent spectral measurements. Plants with higher chlorophyll content tend to produce more stable spectral signals, which reduces variability in sensor readings. This relationship supports the use of spectral sensing for detecting relative differences in plant condition.

The results indicate that nutrient-induced variations in plant physiology can be captured through both SPAD measurements and spectral reflectance patterns. Although the system does not directly quantify biochemical parameters, the consistent relationship between chlorophyll-related indicators and spectral response provides a basis for indirect assessment of plant quality in controlled environments.

Conclusion

This study demonstrates that the AS7265x multispectral sensor provides reliable spectral measurements for plant monitoring in a controlled hydroponic environment after calibration. High linear agreement with the reference spectrometer ($R^2 = 0.9682–0.9870$) confirms that the sensor can capture reflectance trends consistently across the 410–760 nm range, although wavelength-dependent deviations and systematic offsets remain. The sensor successfully preserved key spectral features, particularly in the green and red-edge regions, which are closely related to chlorophyll dynamics. Variations in nutrient concentration were consistently reflected in both spectral responses and SPAD measurements, indicating that the system is sensitive to physiologically relevant changes in plant condition. These results indicate that the AS7265x sensor is suitable for relative plant monitoring and comparative analysis in controlled environments. However, calibration remains essential for quantitative applications due to residual bias and variability across wavelengths. The integration of spectral sensing with physiological indicators provides a practical approach for improving the reliability of low-cost monitoring systems in precision agriculture.

Recommendations

Future research should focus on improving calibration strategies to reduce wavelength-dependent bias and enhance quantitative accuracy, particularly in the green spectral region where higher residual errors were observed. The integration of advanced calibration methods or machine learning-based correction models may further improve sensor performance across varying plant conditions. Further studies are also recommended to expand validation across different crop types, growth stages, and environmental conditions to assess the generalizability of the system. Incorporating additional physiological indicators beyond SPAD, such as biomass or nutrient content, would strengthen the interpretation of spectral data. In addition, the development of real-time decision-support systems based on VIS–NIR sensing is recommended to enhance practical implementation. Integrating spectral monitoring with automated control systems in controlled environments may improve precision in nutrient management and overall cultivation efficiency.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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