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Effect of different photoperiod regimes in combination with natural and artificial light on nutrient uptake in bok choy (*Brassica rapa* L.) using an internet of things-based hydroponics system

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Abstract

In the present study, we analyzed the effect of using a hydroponic system inside a greenhouse and different photoperiod regimes with artificial light on the nutrient uptake of bok choy. Light duration treatment consisting of both sunlight and artificial light was applied to determine the optimal photoperiod for bok choy. Advanced technology—a wireless sensor network and Internet of Things—was used to monitor and maintain nutrient concentrations. Additionally, plant growth was evaluated using image processing technology. A higher amount of P was observed to be accumulated in plants grown in plots without photoperiod. Meanwhile, excessive photoperiod was found to reduce K content in plants. The optimal photoperiod in this study was 20:4 (light:dark), which is a combination of 12 h of sunlight and 8 h of artificial light. Additionally, image processing technology helped monitor plant growth. Pixel information in images can represent plant growth with a R^2 value of >0.8. Further, the addition of photoperiod affects the dry weight of yields and growth rate, which is highly correlated to nutrient uptake, with R^2 values of 0.84 and 0.72, respectively. The combination of artificial light and sunlight along with the optimal photoperiod can optimize the growth of bok choy with appropriate NPK uptake.

Introduction

Healthy lifestyles are gaining tremendous popularity; a healthy lifestyle can be maintained by consuming foods containing vitamins and minerals, such as vegetables. Vegetables contain antioxidants and phytoestrogens as well as possess anti-inflammatory properties, which can reduce the risk of cardiovascular disease, hypertension, and obesity (Dias, 2012; Slavin & Lloyd, 2012). According to the WHO, consuming 400 g of vegetables and fruit per day can improve health and reduce disease risk. Demand for vegetables is increasing owing to population growth; therefore, crop intensification is crucial (Dhakal *et al*., 2021). Conversely, population growth subsequently reduces agricultural land. Uncertain climate change introduces challenges in cropping patterns and thereby influences crop yields. Therefore, hydroponic cultivation is a workable solution to increase food production (Majid *et al*., 2021).

Hydroponics is a cultivation method that does not use soil as a growing medium and instead utilizes nutrient solution and media, such as rock wool, cocopeat, husk charcoal, and several other planting media (Lei & Engeseth, 2021). Hydroponic cultivation techniques facilitate the easy absorption of nutrients by plant roots to maximize growth. Therefore, compared with conventional cultivation methods, subsequent growth rates and yield are expected to improve with hydroponic cultivation techniques (Maketon *et al*., 2020; Sharma, 2019). Another advantage of this method is the ability to grow a higher number of plants within a limited area. Further, hydroponics help in efficient usage of water owing to its closed-loop system. Hydroponic technology in a greenhouse with controlled conditions can minimize crop failure caused by extreme weather changes, such as the long dry season, thereby facilitating sustainable crop production throughout the year (Jenkins *et al*., 2015; Marucci *et al*., 2015; Ruangrak & Khummueng, 2019). Considering these benefits, hydroponics has widely been implemented in vegetable horticultural crops.

The greenhouse is a building concept to protect plants from external environmental conditions that adversely affect plants, such as extreme weather and pests. However, volatile weather causes suboptimal light intensity inside the greenhouse, particularly during the rainy season (Syed and Hachem, 2019). Plants require sufficient light because light is the most important environmental factor driving vegetable yield and quality. In greenhouses, artificial light can be an alternative light source to aid photosynthesis when the intensity of incoming light decreases (Chaichana *et al*., 2020). Efforts to increase horticultural crop production involve the application of various types of light and photoperiod regimes (Díaz-Galián *et al*., 2021). Artificial light using LEDs has advantages over traditional lamps because they are more energy efficient for plant photosynthesis. Different LED colors produce different wavelengths and effects on plant growth and development. Both red and blue light are efficiently absorbed by chlorophyll a and b (Kaiser *et al*., 2019) and red light can increase the weight and height of strawberries (Nadalini *et al*., 2017). Another study showed that combining red and blue light simultaneously can result in optimal fruit production. A study has shown that combining red and blue LEDs for 16 h can increase plant height, leaf size, and stem length (Naznin *et al*., 2016).

Technology developed for the agriculture field aims to increase efficiency and effectiveness and includes remote sensing (RS), Internet of Things (IoT), artificial intelligence, wireless sensor networks (WSN), and computer vision (CV) to collect agronomic data related to crop conditions and decision making. RS and CV technology are closely related and utilize cameras to capture plant images and obtain data, such as the level of leaf greenness and the physical aspects of the plant (Swain *et al*., 2010; Makky, 2016). In the field of indoor agriculture, WSN and IoT have widely been applied to automatic watering systems and mechanisms for monitoring environmental conditions in greenhouses. In addition to the environmental monitoring system, in indoor cultivation, a nutrition control system such as hydroponics is also required (Kim *et al*., 2013).

Plants require two types nutrients—macro and micro. Macronutrients are needed in relatively large quantities for plant growth. These macronutrients include nitrogen (N), phosphorus (P), and potassium (K). N is absorbed by plants in the form of nitrate ions (NO^{3-}) and ammonium ions (NH^{4+}) (He *et al*., 2020). Nutrient N plays an important role in the vegetative phase of plants, namely for the growth of leaves and stems and for maintaining the green color. Moreover, this element is essential in the formation of chlorophyll, which is involved in photosynthesis by plants (Aminifard *et al.*, 2012). An N deficit can cause slow or delayed leaf growth as well as lead to the leaves becoming small and less green, turning yellow, and drying. The element P is absorbed in the form of H_2PO^{4-} and HPO^{4-} ions by plants. P plays a role in the growth and development of plant roots until the reproductive phase. Plants require P to increase the number of root nodules that can stimulate a more optimal nutrient absorption. Plants absorb the element K in the form of K^+ ions. K plays a role in photosynthesis, osmotic adjustment, cell growth, stomata regulation, and plant water systems (Sardans & Peñuelas, 2021). Hydroponic cultivation methods typically use AB-mix compound fertilizer, which contains complex nutrients as well as macronutrients and micronutrients required by plants (Harahap *et al*., 2020). Bok choy is a type of vegetable plant that requires sufficient light for photosynthesis, whereby light intensity and N concentration significantly affect its growth and yield (Hao *et al*., 2020). Nitrogen and light influence photosynthetic activity in plants by affecting its chlorophyll content. Plant health can be estimated using RS and CV technology. By estimating N levels in plants, we can measure N uptake.

Nutrient (NPK) uptake by plants is affected by several factors, including plant age, plant size, and root size, as well as by the ability of roots to absorb water and nutrients from the growth media. Moreover, light required by plants influences its growth through photosynthetic metabolism. Owing to varying light intensities, plant nutrient uptake will differ for each growth phase (Bodale *et al*., 2021). According to Hao *et al*. (2020), nutrient and light concentrations affect bok choy growth.

Nutrient levels according to plant needs can increase profits and yields for farmers and reduce the negative impact of excessive plant fertilizer. However, studies on nutrient (NPK) uptake by bok choy cultivated using hydroponic techniques under varying light durations are limited. By calculating nutrient (NPK) uptake, plant nutrient requirements can be estimated to ultimately increase nutrient efficiency.

Light intensity and duration are essential for plant growth. Zheng *et al*. (2018) reported that blue light intensity can increase the accumulation of leaf vegetable biomass in greenhouses. For example, light intensity influences fresh biomass in spinach (Najera & Urrestarazu, 2019). Further, high light intensity and low temperature can increase the growth of tomatoes cultivated in plant factories (Song *et al*., 2022). Several studies (Biradar *et al*., 2018; Johnson *et al*., 2012; Liu *et al*., 2022) have documented the impact of light intensity using artificial light or natural light on the quality and yield of bok choy. In addition to light intensity, irradiation or photoperiod length affects growth during the vegetative phase of plants. However, studies on the combined impact of artificial and natural light are limited.

To fill these gaps and provide solutions for precise and sustainable agriculture, in the present study, we analyzed the effect of different lighting durations with LED as artificial light combined with sunlight on crop yield. We observed multiple parameters—plant physiology, environmental conditions, light intensities, chemical plant properties pertaining to N, P, and K absorption—as well as their relationship to crop yield. Moreover, advanced technologies (RS, IoT, CV, and artificial light) were implemented for monitoring bok choy inside the greenhouse. This study aimed to evaluate the efficiency of using fertilizers (NPK elements) under different nutrient regimes and light intensities in hydroponic systems. Specifically, we aimed for the following: 1) to document the use of a hydroponic system, 2) to evaluate the effect of LED artificial light on plant agronomy, and 3) to evaluate the chemical properties of bok choy using RS and CV.

Materials and Methods

Experimental setup

The present study was conducted in a greenhouse located at the University of Jember, Indonesia (−8.1617393, 113.7093914), using seven hydroponic installations. Each plot was 1 × 2 m with 55 planting holes in each installation (Figure 1). The pipe diameter used in the installation was 3 inches. The planting medium was 2.5 × 2.5 cm of rockwool with a dry weight of 2.7 g. This study used the Nauli variety of bok choy; each plot included 55 plants.

All sides of the greenhouse were closed using an insect net, which aimed to prevent pests and maintain air circulation. Additionally, shade was provided by installing 60% paranet on the roof, thereby allowing only 40% of sunlight to penetrate. Being a vegetable plant, bok choy requires lower temperatures and proper light intensity for optimal growth (Wijaya *et al*., 2019). However, when weather conditions are cloudy, light intensity entering the greenhouse decreases, thereby necessitating artificial light. There were seven different light treatments in the present study: 2, 4, 6, 8, 10, and 12 h and no artificial light (Table 1). Artificial light comprised red and blue light in a ratio of 5:1; the light source was placed 60 cm above the installation pipe. The light intensity produced by the LED artificial light was 133 μm m^{-2} s^{-1}, which was measured perpendicular to the LED artificial light at a distance of 60 cm. A 2-mm-thick black mat was used as a barrier to avoid light leakage between treatments. The artificial light source was instantaneously switched on when the greenhouse no longer received sunlight, namely, at 6:00 pm, and was switched off according to the setpoint for each treatment.

A pH sensor and a solenoid valve were used to maintain pH levels for nutrient solutions. Two solenoid valves accommodated different solutions—pH-Low and pH-High. To lower the pH of the nutrient solution, a pH-Low solution containing phosphoric acid was used, whereas to increase pH, a pH-High solution containing potassium hydroxide was used (Mehboob *et al*., 2019). The setpoint for the pH maintenance system was set to 6–7. When pH in the nutrient solution fell below 6, the solenoid valve on the pH-High solution was activated until pH level reached 6–7. Conversely, when pH was above 7, the solenoid valve on the pH-Low solution was activated until pH level reached 6–7. The treatment was performed until the bok choy were harvested at 42 day after transplanting (DAT). AB-mix used in the present study contains N (18.1%), P (5.1%), K (25.3%), Ca (14.2%), Mg (5.35), S (13.6%), Fe (0.1%), Mn (0.05%), Cu (0.05%), and B (0.03%).

System preparation

An energy-independent greenhouse, utilizing solar panels as the main source of electrical energy, was used in the present study. Solar panel capacity was set to 100 WP with a battery capacity of 12 V and 70 A. This study involved several systems, including environmental monitoring, nutrition monitoring, plant imaging, networking, and machine learning systems (Liao *et al*., 2017). Several factors inside the greenhouse, such as air temperature, humidity, and daily light intensity, were measured for environmental monitoring. Additionally, sensors for pH, TDS, water temperature, water level, and pressure were used for monitoring and maintaining nutrient solutions. Further, we employed an automated system for water circulation. Therefore, the water pump was only activated according to the specified schedule. To regulate water circulation, the water pump was switched on for 30 min, then shut off for 3 h. The pump was operated at 6:00 am daily. The pump scheduling aimed to manage the existing electrical resources (da Silva *et al*., 2016).

A low-end device with associated features, such as routing, firewall, DHCP, and VPN, was the networking system used in the present study. Communication between the microcontroller and the server required a VPN connection. The IoT system in this study was used to monitor and control environmental factors and nutrient solutions in real-time (Figure 2).

Measurements

Several plant parameters were measured to determine the effect of environmental conditions, particularly that of artificial light on the growth of bok choy using hydroponic techniques. These parameters were measured using both destructive and non-destructive methods. Environmental parameters analyzed using IoT were air temperature, relative humidity (RH), light intensity, solution concentration, and solution pH. The vegetation index was measured using a camera. Furthermore, plant properties were observed using a spectrometer and SPAD-502 Chlorophyll meter with a direct measurement method for plant organs (leaves) (Beghi *et al*., 2017). The destructive method was used for laboratory analysis.

Physical measurements

Plant physical parameters included plant height (cm), leaf number, canopy width (cm), and leaf width (cm) observed at 7, 14, 21, 28, 35, and 42 days after transplanting (DAT). Root volume (g) was assessed during the harvest period, which was 45 DAT. Parameters for wet plant weight (g) and dry plant weight (g) were measured at 28 DAT and 42 DAT to determine plant growth rate. The equation used to measure plant growth rate (LPT) was as follows:

$$LPT = \Delta W / \Delta t \quad (1)$$

$$\Delta W = W2 - W1 \quad (2)$$

$$\Delta t = t2 - t1 \quad (3)$$

where:

LPT: Plant growth rate

W2 : Dry weight (roots and shoots) at *t2* observation

W1 : Dry weight (roots and shoots) at *t1* observation

$t1$: 1st observation

$t2$: 2nd observation

Above-canopy measurements

Five bok choy plants from each plot were used as samples for image analysis using an RGB camera (Canon IXUS 160) (Putra *et al.*, 2021). Images were captured using a customized lighting system (Figure 3A); image data collection of bok choy was performed at 14, 21, 28, 35, and 42 DAT.

Direct leaf measurements

An optical-based measurement method was used to measure plant properties. Direct leaf measurement was obtained using a portable fiber optic spectrometer (ASEQ Instrument) with a halogen lamp as a light source (Figure 3B) and a SPAD 502 chlorophyll meter (Figure 3C). The sample leaf was the third leaf in each pot (Putra *et al.*, 2018). For each plot, 10 leaves were collected and evaluated to determine the reflectance value of the measurement results using a fiber optic spectrometer. Measurements using the spectrometer and SPAD chlorophyll meter were performed on 14, 21, 28, 35, and 42 DAT.

Vegetation indices

The vegetation index (VI) was used to analyze camera images and measurements using a portable fiber optic spectrometer (Cho *et al*., 2007). VI is a description of vegetation properties that are indicative of plant greenness, which was documented during image transformation. Plant spectral values were mathematically calculated to determine variations in continuous spatial data from leaf vegetation. VI obtained from RS-based canopy data was essential for the quantitative and qualitative evaluation of vegetation cover; plant growth was interpreted as differences and changes in leaf green color and canopy spectral characteristics (Xue & Su, 2017). VI analysis in the study is presented in Table 2.

Laboratory analysis

We implemented a destructive analysis test using a chemical mechanism to analyze N, P, and K (Figure 3D). Kjeldahl analysis was used to determine N content in the plants, whereas the wet digestion method was applied to determine P and K contents (Pequerul *et al*., 1993). Laboratory analysis was performed at the Indonesian Coffee and Cocoa Research Center. Sampling for analysis was performed at 42 DAT when bok choy was harvested; chemical analysis was performed on five sample leaves collected from five plants for each treatment.

NPK uptake

In the present study, we analyzed the effect of photoperiod regimes on NPK uptake or efficiency of NPK use. Evaluating NPK uptake for plants is important to determine optimal nutrient concentrations required to minimize nutrient deficiencies, reduce the negative impact of excessive fertilizer use, and reduce production costs for purchasing fertilizers (Wen *et al*., 2022). The following equation was used to estimate uptake of N, P, and K elements:

$$Nutrient\ Uptake(kg\ ha^{-1}) = \frac{Nutrient\ Content\ (\%)\ x\ Dry\ Weight\ in\ kg\ ha^{-1}}{100} \quad (4)$$

Statistical analysis

Jupyter Notebook software was used for data analysis. To generate the model, data were analyzed using regression analysis to identify the coefficient of determination (R^2) and root mean square error (RMSE). RMSE was calculated using the following equation:

$$RMSE = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (Pi - Oi)^2} \quad (5)$$

where Pi, Oi, and n were the predicted value, observed value, and the number of samples tested, respectively. For analyzing the effect of treatment on plant morphology, ANOVA test was used to determine the significance of the differences in each treatment, following by Duncan test (α = 5%).

Results and Discussion

In the present study, environmental parameters and plant growth data for each treatment were collected and analyzed. Environmental parameters including air temperature, humidity, light intensity, nutrient pH, and nutrient concentration (ppm) (Harahap *et al*., 2020; Suwitra *et al*., 2021), were collected using a system powered by IoT. Physiological plant growth was observed, including plant height, number of leaves, and plant weight; these parameters were used to evaluate the effect of artificial light irradiation on bok choy under hydroponic cultivation.

Spectral characteristics of artificial light

Cultivation techniques in a controlled chamber/greenhouse can provide sufficient light for photosynthesis during each plant growth phase. Plants can be etiolated if light intensity decreases. However, excessive light intensity can cause photoinhibition. Both these phenomena can disrupt primary productivity in plants. During photosynthesis, chlorophyll can absorb waves of 400–500 nm and 600–700 nm. These wavelengths correspond to blue and red light; thus, these waves should be emitted by artificial light designed for plant growth (Wijaya *et al*., 2019). Research on photosynthesis under artificial light has gained traction in the literature. Agronomically, artificial light can meet the light requirements of plants; wavelengths produced by artificial light can be modified to produce the quantity and quality of light required at different growth phases. In artificial light, red light with a wavelength of 650–665 nm is suitable for chlorophyll and phytochrome absorption in plants. Meanwhile, the addition of blue light with a wavelength of 460–475 nm can activate cryptochrome, which is a plant photoreceptor. Compared with monochromatic light, the combination of blue and red light results in a higher photosynthetic activity (Darko *et al*., 2014). The wave characteristics documented in this study are shown in Figure 4.

Acquiring environmental parameters

Environmental parameters in the greenhouse were observed on a daily basis, which included air temperature (ºC), RH (%), light intensity (lux), pH, and nutrient concentration represented by TDS (ppm). These data were recorded using an IoT-based system (Figure 5). Nutrient concentration and pH are essential factors in hydroponic cultivation. Each phase of plant growth under different nutrient concentrations requires the maintenance of appropriate nutritional needs to prevent nutrient deficiency and overdose (Miller *et al*., 2020). Plant growth rates in each plot varied owing to differences in photoperiod application. To achieve consistent concentrations, the amount of AB-mix nutrition and water applied in a single growing season varied with each plot. The maintenance of AB-mix nutrition and pH was controlled automatically using the IoT. Figure 5 shows stable TDS and pH levels.

Additionally, implementing a shade net in the greenhouse affects temperature, humidity, and light intensity. Shade nets can reduce greenhouse temperature throughout the day (Angmo *et al*., 2021; Díaz-Pérez, 2013). Applying shade nets increases RH and reduces incoming solar radiation.

Morphological characteristics of different treatments

Parameters observed in plant growth included plant height (cm), leaf number, canopy width (cm), fresh weight (g), dry weight (g), growth rate (g day^{-1}), leaf width (cm), and root volume. Parameters were periodically measured at 1, 7, 14, 21, 28, 35, and 42 DAT; the allometric approach method was used to estimate plant nutrient (Jing *et al*., 2020) and biomass (Kebede & Soromessa, 2018) accumulation. Moreover, the effect of photoperiod lighting duration on growth, production, and plant properties of bok choy was evaluated. According to Xu *et al*. (2020), photoperiod can significantly affect plant height, dry weight, roots, and plant chlorophyll content. Based on observational data of plant physical parameters, compared with treatment without adding artificial light, treatment with additional 8-h photoperiod using LED resulted in a higher fresh weight, number of leaves, plant height, leaf width, canopy width, dry weight, and roots. These results are consistent with the results obtained by Adams & Langton (2005), which state that all-day treatment produces larger leaves. Adding photoperiod also resulted in taller plants.

Figure 6 shows the growth chart during a single bok choy growing season. Plant growth is influenced by climatological factors. The present study was conducted during the rainy season from February to April, with fluctuating sunlight. Therefore, the addition of a photoperiod using LED artificial light was necessary to provide optimal lighting for plants. The light intensity of the artificial light was 133 $\mu m\ m^{-2}\ s^{-1}$, which was perpendicularly measured with a distance of 60 cm between the artificial light and installation pipe. Based on observations of plant morphological characteristics, the addition of a photoperiod with artificial light for 8 h (Plot 4) showed better results. However, this finding does not indicate that a longer duration of lighting will produce better morphological parameters. As shown in Figure 6, some of the morphological characteristics of plants receiving 10 and 12 h of lighting were lower than those of plants receiving 8 h because an optimal environment is essential for plant growth. In addition, photoperiod requirements will differ based on the plant varieties. These findings are supported by several photoperiod studies on various plants that acknowledge different optimum photoperiods for each type of plant (Azmi *et al*., 2015). Based on the results of the ANOVA and Duncan tests (Table 3), the photoperiod treatment resulted in a significant difference.

Direct leaf and above-canopy measurements

Periodic measurements for monitoring plant growth were performed using above-canopy and direct leaf measurements. Photoperiod affects chlorophyll content in plants; this content is correlated with N content and leaf greenness, which can estimate plant health. Treatment in plots 1–7 after the addition of different LED photoperiod regimes was administered for 0, 2, 4, 6, 8, 10, and 12 h and observed using a portable spectrometer and an RGB camera. Periodic measurements were obtained on 14, 21, 28, 35, and 42 DAT. Data collection using a spectrometer helped estimate leaf greenness, which correlated with chlorophyll content (Putra *et al*., 2021). Spectral values of bok choy at 28 and 42 DAT are presented in Figure 7. Based on observational results, photoperiod treatment led to different levels of greenness, which was evident in values of the green color spectrum (550 nm) and near-infrared waves (800–850 nm) (Buschmann *et al*., 2012; Sabri *et al*., 2019).

Chlorophyll content, indicated by leaf greenness level, was estimated using a non-destructive method with a portable fiber optic spectrometer. However, this method did not encompass all leaf information because it was only performed on a few sample points. For comparison, the above-canopy measurement method relying on images from the RGB camera was used. This measurement method can cover a wider ROI and provide information on greenness level, plant growth, and development based on the pixel ratio of captured images. Bok choy image data are presented in Figure 8.

Measurements were obtained with the direct leaf measurement method using a fiber optic portable spectrometer and an RGB camera (Table 4); plot 3 shows the best results as shown by the spectrum describing the highest greenness level. Additionally, Vis were aligned with the spectral signature of plant leaves in each plot. Moreover, among all plots, the data showed that Vis in plot 3 were the highest. Further, green leaf color is influenced by chlorophyll content (Samseemoung *et al*., 2017). A study conducted by Kang *et al*. (2013) on vegetable crop cultivation in plant factories reported that a photoperiod with a light:dark ratio (9:3) or 18 h of lighting can increase photosynthesis rate and chlorophyll content in leaves.

However, measurements obtained with the above-canopy method using the RGB camera provide a more visible difference among plots, demonstrating that plot 4 shows the best results based on the pixel ratio between plant object and frame. Direct leaf measurements are limited owing to narrower ROI areas, thereby restricting observations to only within the measured points. Additionally, only spectral data can be obtained based on leaf greenness level. Figure 8 shows images of bok choy captured using an RGB camera; there is a significant increase in plant size, number of leaves, and leaf size of bok choy at every 7 DAT.

This is further supported by Figure 9 that presents a pixel ratio comparison between plants and image background and shows a consistent increase. Based on pixel ratio analysis, plot 4 shows the optimal bok choy production, which correlates with the measurements of several physical plant parameters (corresponding to Figure 6). The parameter that exerts the greatest effect on pixel ratio is canopy cover, which is influenced by leaf size.

Correlation between ground-based remote sensing and plant properties

Plant canopy images captured using an RGB camera provide information on physical plant growth that can be observed continuously. Plant growth can be identified by comparing pixels of plants against the image background, whereby pixel ratio is directly proportional to growth of bok choy. The correlation coefficient between pixel ratio and physical growth of bok choy included properties such as plant weight (g), number of leaves, plant height (cm), leaf width (cm), canopy width (cm), and dry weight (g), which were determined to have a R^2 of 0.89, 0.85, 0.82, 0.90, 0.81, and 0.74, respectively. A study conducted by Fanourakis *et al*. (2014) showed that pixel ratio is directly proportional to plant physical growth. Figure 10 presents the correlation between pixel ratio and physical growth of bok choy.

Evaluation of nutrient uptake following photoperiod treatment

Light significantly influences the growth and development of vegetable crops. Adjusting light levels to improve nutrient uptake capacity of plants can help to increase profits (Xu *et al*., 2021). In agricultural activities, the proper application of plant nutrients is required to increase crop yield and vegetable quality. However, excessive fertilizer use has a negative impact. Therefore, efficient fertilizer use is crucial (Mansoorkhani *et al*., 2014; Li *et al*., 2018). This study used a hydroponic cultivation technique using AB-mix fertilizer that contains compound nutrients for plants and analyzed the impact of photoperiod with artificial light LEDs on the absorption of NPK elements.

Destructive analysis of plant organs was conducted to determine NPK content (Table 5). Higher N content was observed in the plot with photoperiod treatment, whereas lower N content was noted in plots without photoperiod treatment. These results corroborate with those of Xu *et al*. (2020), which acknowledge that photoperiod affects chlorophyll content in plant leaves and is highly correlated with uspidat uptake. In the present study, we found the highest and lowest N content in plots 4 and 7, respectively. Additionally, for P content, compared with plots with photoperiod treatment, those without photoperiod treatment showed a higher P content. According to Wu *et al*. (2021), environments with suboptimal lighting can stimulate P accumulation in plant tissues. For K levels, the lowest and highest K content were observed in the 12-h photoperiod treatment (plot 6) and without photoperiod addition (plot 7), respectively. These results reflect those of Ainun *et al.* (2018), who showed that continuous lighting reduces K, Ca, and Mg content in plants.

Under artificial light, plants have a higher duration for photosynthesis and a higher chlorophyll content index. Light exposure increases N uptake via gene transcription associated with N uptake (Li *et al*., 2020). Table 6 shows estimated nutrient (NPK) uptake in one growing season. Photoperiod treatment with LED for 8 h (plot 4) resulted in the highest nutrient uptake for each element (N, P, and K). The driving factors of nutrient uptake are plant dry weight and element levels in the fertilizer (Rao Puli *et al*., 2019; Wen *et al*., 2022). The lowest nutrient uptake was observed in plots without photoperiod treatment, indicating that photoperiod marked affects plant growth and nutrient uptake (Adams & Langton, 2005).

Moreover, nutrient uptake is highly correlated with dry weight of yields and growth rate, with R^2 values of 0.84 and 0.72, respectively (Figure 11). Additionally, dry weight of yields and growth rate can be represented by pixel ratio obtained using ground-based RS (Rao Puli *et al*., 2019; Wen *et al*., 2022).

Conclusions

Light is an essential environmental factor affecting plant growth. Unstable weather conditions affect the amount of sunlight received by plants for photosynthesis, typically resulting in suboptimal growth outcomes. Here, using LED artificial light is an alternative solution to meet required light intensities. LED artificial light allows farmers to adjust photoperiods to obtain optimum photoperiod treatment according to commodity type. In the present study, advanced technologies, such as WSN, the IoT, and image processing integrated into a sensing system, were used for plant monitoring and maintaining nutrient concentrations administered during plant cultivation using hydroponic technology in a greenhouse.

We evaluated growth and nutrient uptake of bok choy as a result of different photoperiod treatments. The results show that photoperiod with LED affects the physical growth of plants, which can be observed using image processing technology. Plant images provide pixel ratio information that highly correlated with the physical growth of plants using $R^2 > 0.8$. Photoperiod affects plant dry weight, which is correlated with nutrient uptake in plants with an R^2 of 0.84. Additionally, nutrient uptake correlates with plant growth rate with an R^2 of 0.72. A photoperiod of 20:4 (light:dark) combined with 12 h of sunlight and 8 h of LED artificial light is the optimal photoperiod for the hydroponic cultivation of bok choy, particularly in tropical areas.

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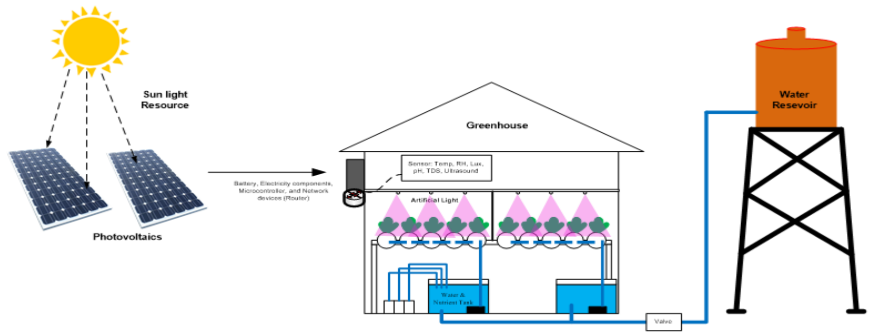
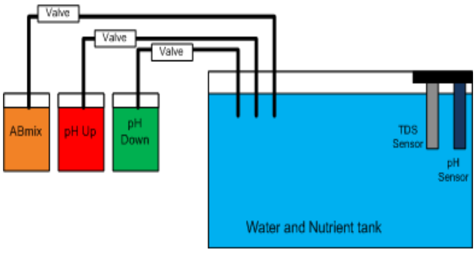


(a)



(b)

Figure 1. Greenhouse experimental setup. (a) Greenhouse system; (b) automated system for nutrient and pH maintenance.

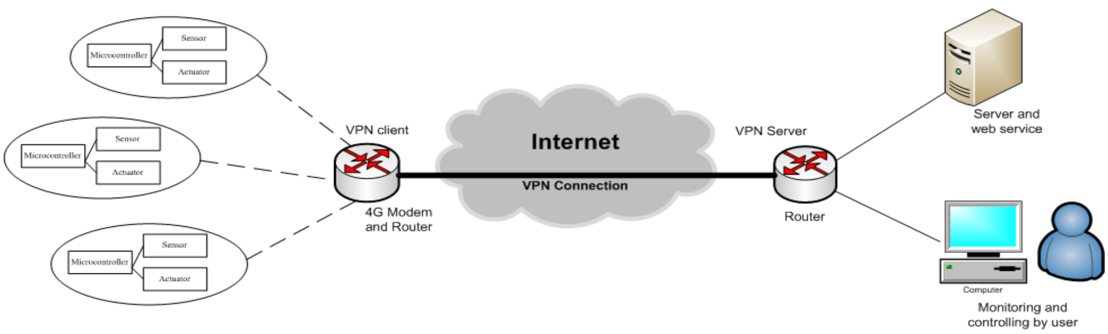
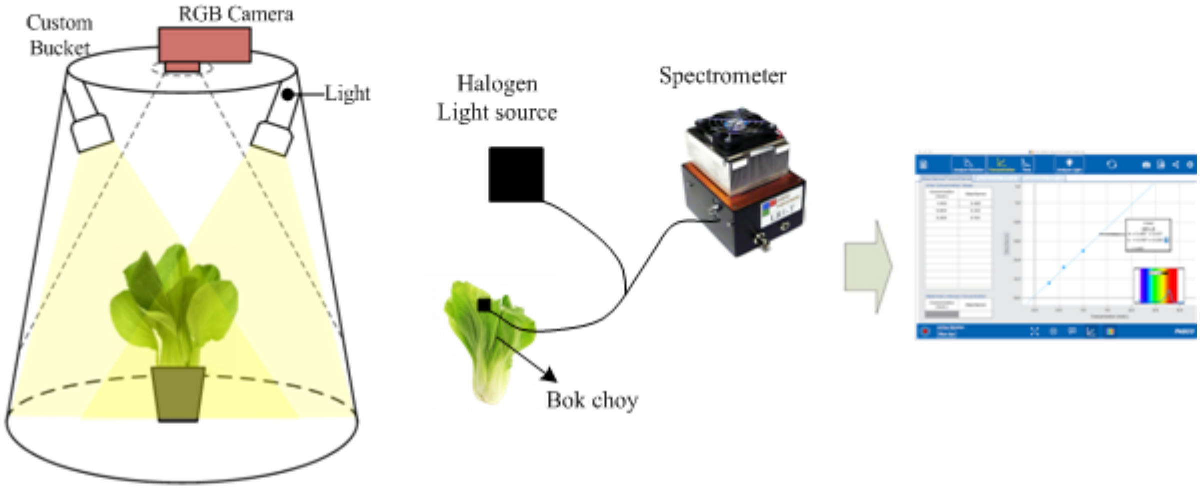


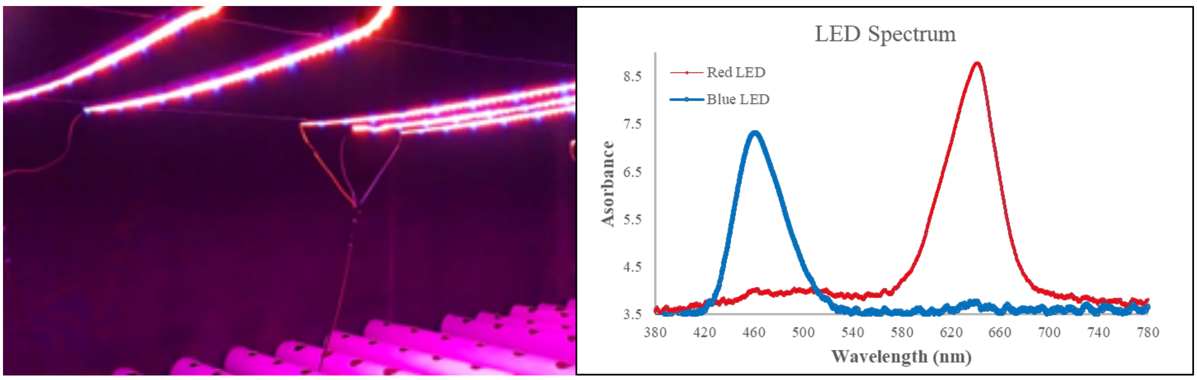
Figure 2. IoT system architecture and preparation.



(a) (b)

(11) (d)

Figure 3 Measurement: (a) Custom bucket for image data acquisition using RGB camera; (b) direct leaf measurement using portable fiber optic spectrometer; (c) direct leaf nitrogen analysis using SPAD chlorophyll meter; (d) chemical analysis to determine N, P, and K contents.



(A) **(B)**

Figure 4. Implementing LED inside a greenhouse: (A) Installed LED; (B) wavelength of LED artificial light.

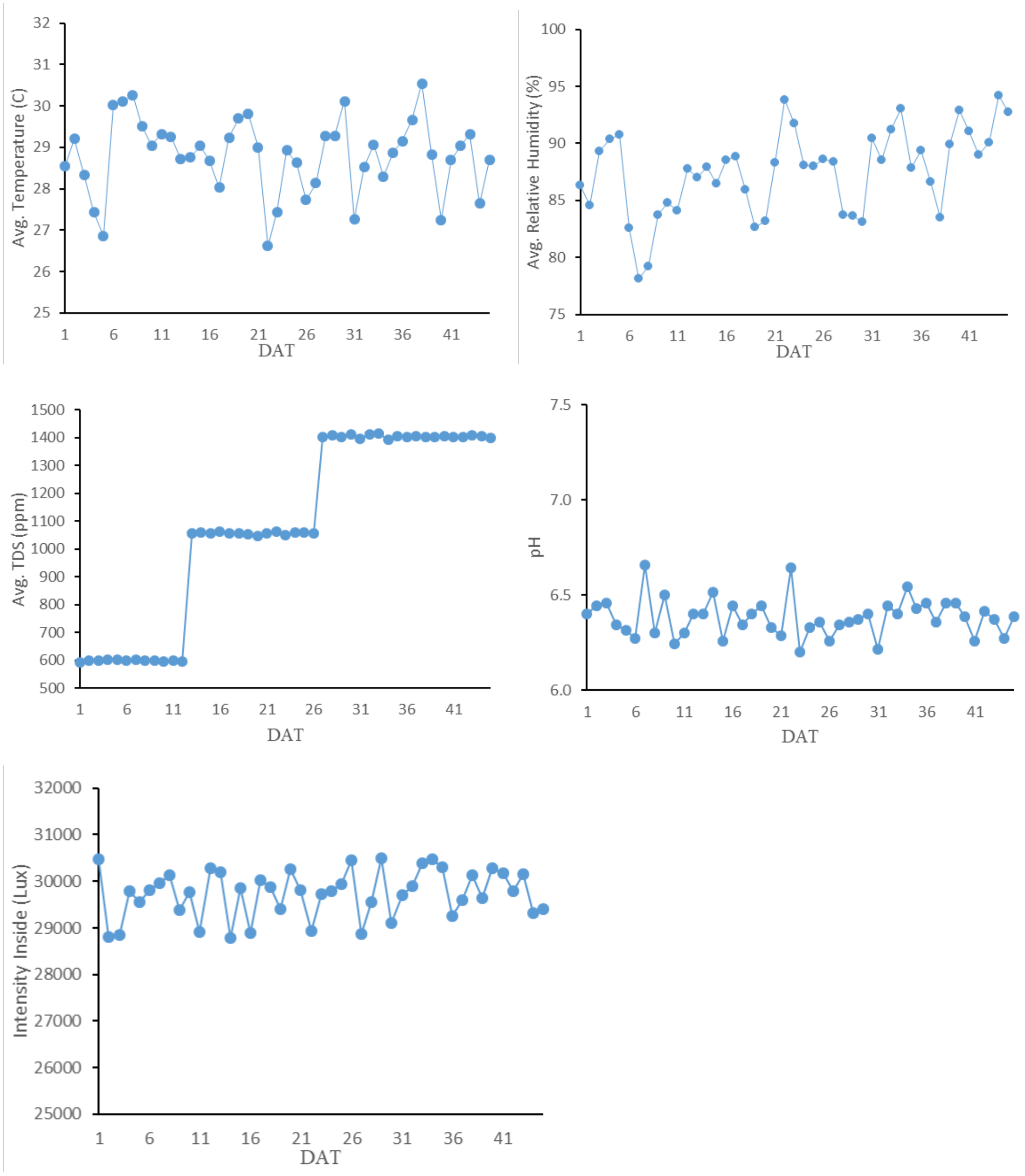


Figure 5. Environmental parameters for one growing season.

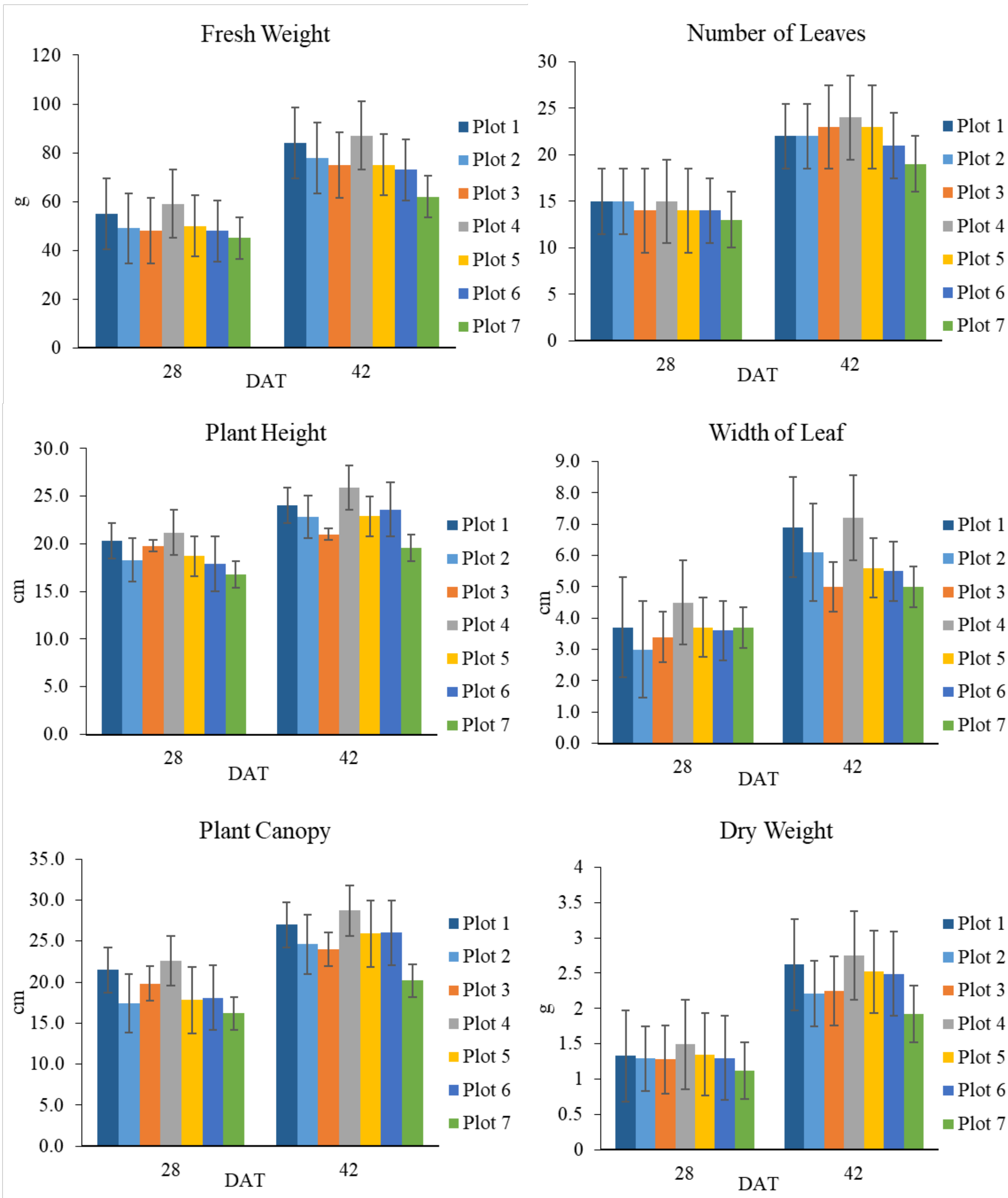


Figure 6. Plant physical properties using manual measurements.

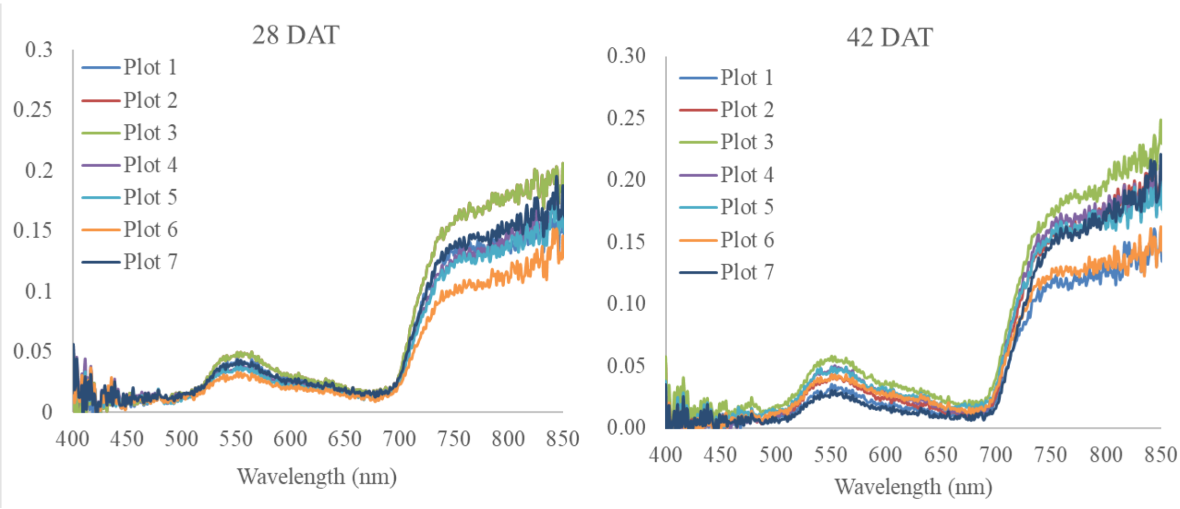


Figure 7. Spectral signature of bok choy.

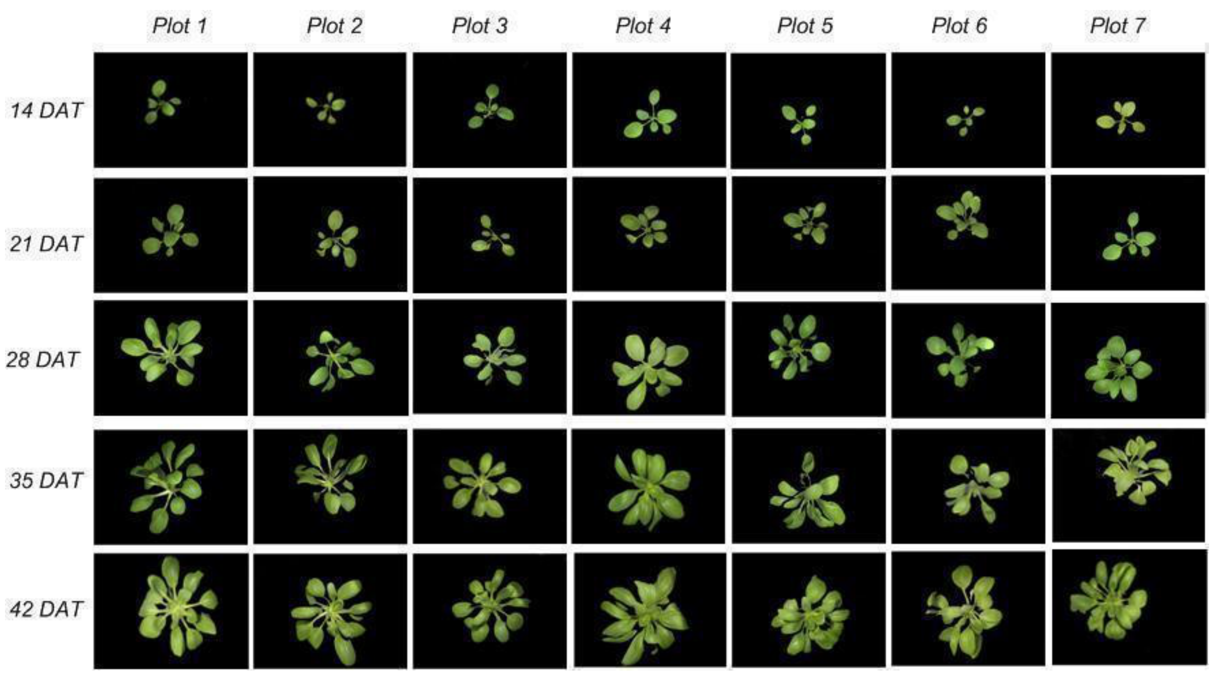


Figure 8. RGB images of bok choy.

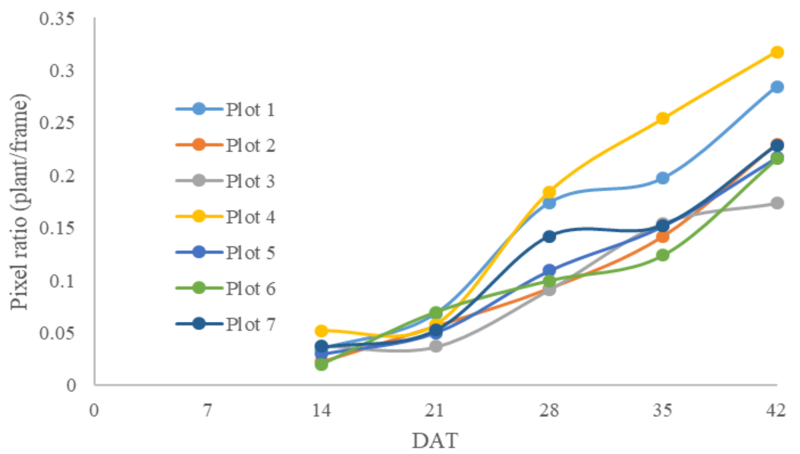


Figure 9. Correlation between pixel ratio at different stages.

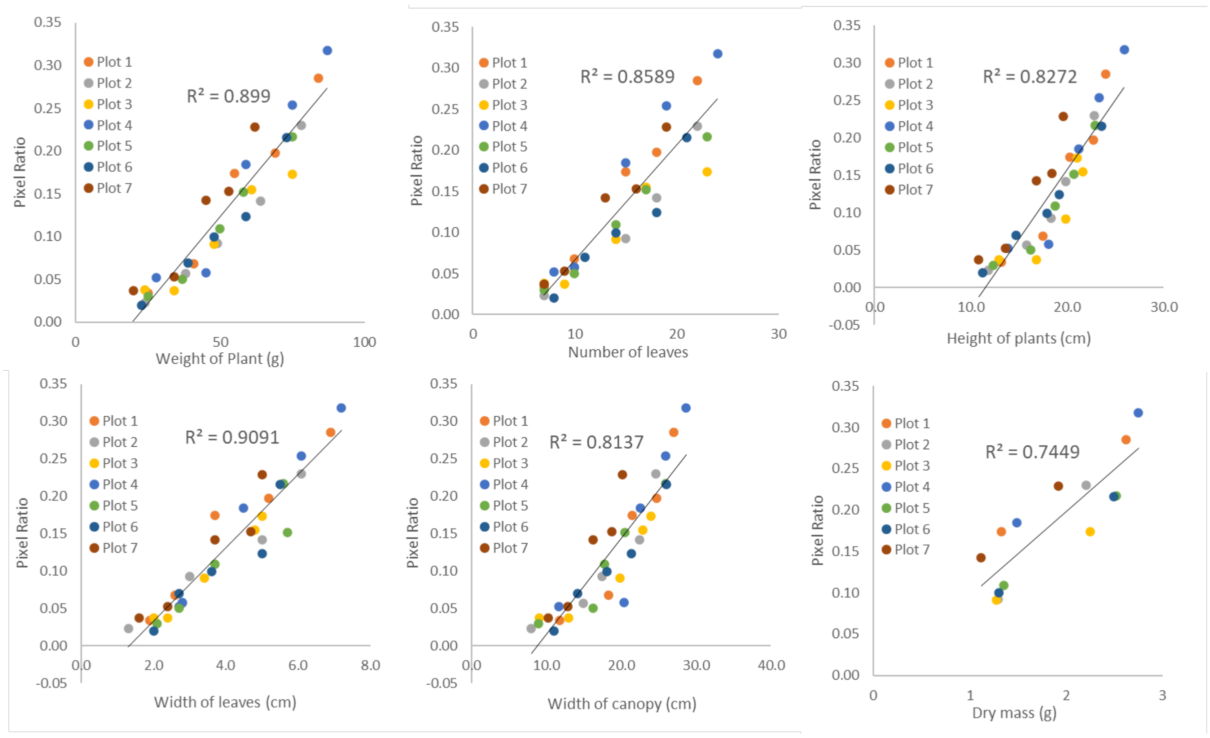


Figure 10. Correlation between plant properties and ground-based remote sensing.

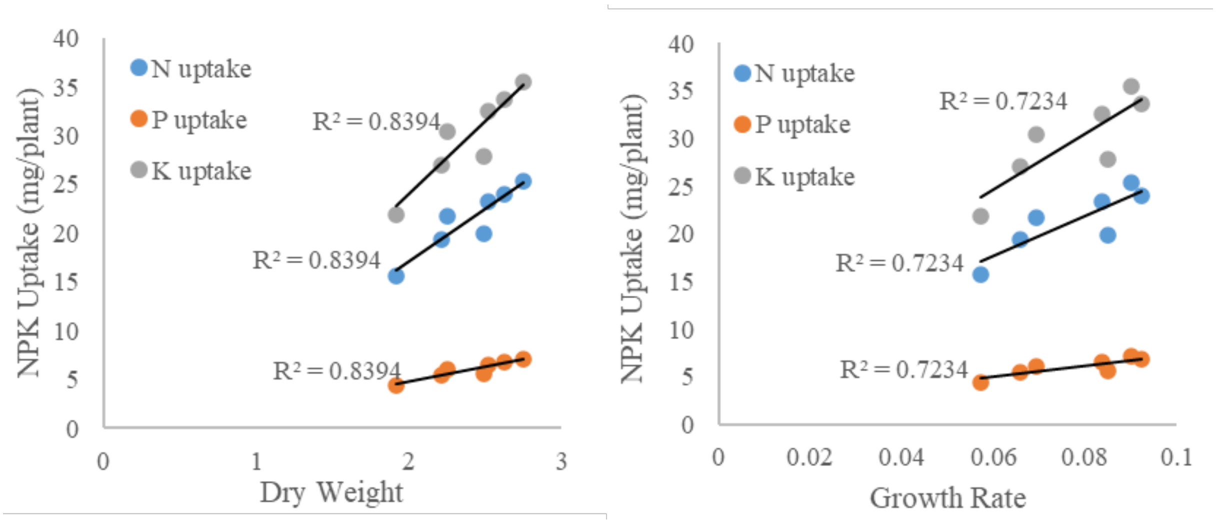


Figure 11. Correlation between NPK uptake with dry weight and growth rate.

Table 1. Experimental setup of artificial light application in plots.

Plot no.	Artificial light treatment	Time		Fertilizer treatment (ppm)		
		Light on	Light off	1 DAT	13 DAT	27 DAT
1	sl + 2h al	6 pm	8 pm	600	1050	1400
2	sl + 4h al	6 pm	10 pm	600	1050	1400
3	sl + 6h al	6 pm	00 am	600	1050	1400
4	sl + 8h al	6 pm	2 am	600	1050	1400
5	sl + 10h al	6 pm	4 am	600	1050	1400
6	sl + 12h al	6 pm	6 am	600	1050	1400
7	sl + 0h al	-	-	600	1050	1400

sl = sunlight; al = artificial light

Table 2. Vegetation indices used for RGB camera and spectrometer.

Vegetation index	Formulas	Instrument	Remark
NDVI rgb	$NDVI\ rgb = \frac{(g+b)-r}{(g+b)+r}$	RGB Camera	Broadband
VARI	$VARI = \frac{g-r}{g+r-b}$	RGB Camera	Broadband
NDVI	$NDVI = \frac{NIR-R}{NIR+R}$	Spectrometer	Narrowband NIR = 770–785 nm and R = 660–675 nm

Table 3. The results of the ANOVA and 'Duncan tests (α = 0.05).

Parameters	Treatments						
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7
Fresh weight (g)	84.00e*	78.00d*	75.00c*	85.67f*	75.00c*	73.00b*	62.33a*
Number of leaves	22b*	22b*	23b*	23b*	22b*	21b*	19a*
Plant height (cm)	24.00c*	22.80c*	21.00b*	24.00c*	22.90c*	23.60c*	19.60a*
Width of leaf (cm)	6.90c*	6.10b*	5.00a*	7.20c*	5.60ab*	5.50ab*	5.00a*
Canopy (cm)	27.00d*	24.60bc*	24.00b*	28.70e*	25.90cd*	26.00cd*	20.20a*
Dry weight (g)	2.62de*	2.18b*	2.25bc*	2.75e*	2.52de*	2.46cd*	1.92a*

a; b; c; d; e is the rank from Duncan test result. * indicates significant difference ($P < 0.05$)

Table 4. Comparison of Vis using an RGB camera and spectrometer.

DAT	VI	Instrument	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7
28	NDVI	Camera	0.267	0.288	0.377	0.270	0.311	0.328	0.318
	VARI	Camera	1.415	1.431	1.640	1.315	1.483	1.429	1.377
	NDVI	Spectrometer	0.786	0.811	0.811	0.779	0.810	0.780	0.792
42	NDVI	Camera	0.268	0.240	0.298	0.240	0.247	0.208	0.240
	VARI	Camera	0.465	0.437	0.531	0.400	0.523	0.446	0.450
	NDVI	Spectrometer	0.786	0.811	0.811	0.779	0.810	0.780	0.792

Table 5. NPK destructive analysis.

Substance	Lab analysis (Plot No.)						
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7
N	4.69	4.62	4.91	5.33	4.91	4.69	4.34
P	0.52	0.40	0.28	0.52	0.26	0.40	0.57
K	4.23	1.90	2.78	4.25	1.00	0.92	5.01

Table 6. Nutrient uptake.

Nutrient Uptake (mg plant^{-1})	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7
N uptake	24.06	19.34	21.73	25.41	23.30	19.92	15.68
P uptake	6.78	5.45	6.12	7.16	6.57	5.61	4.42
K uptake	33.64	27.03	30.38	35.52	32.57	27.84	21.92