Way to boost lettuce yields and quality by incorporating movable downward lighting with a supplemental adjustable sideward lighting system in a plant factory (#80778)

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Way to boost lettuce yields and quality by incorporating movable downward lighting with a supplemental adjustable sideward lighting system in a plant factory

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Background: Lettuce is a vegetable that is increasingly consumed globally, given its nutritional quality. Plant factories with artificial lighting can produce high-yield and high-quality plants. The high plant density in these systems speeds up leaf senescence. Wasted energy and lower yield raised labor expenses are some of the bottlenecks associated with this farming system. Therefore, using artificial lighting, it is crucial to develop cultivation techniques that would boost lettuce yields and quality in the plant factory.

Methods: Romaine lettuce was grown under the developed "movable downward lighting combined with supplemental adjustable sideward lighting system "(C-S) and under a system without supplemental sideward lighting (N-S) in a plant factory. The effects of C-S on lettuce's photosynthetic characteristics, plant yield, and energy consumption relative to plants grown under a system without supplemental sideward lighting (N-S) were studied.

Results. The study demonstrated that using the C-S in plant factories can promote photosynthesis, reduce light energy consumption, and delay senescence, boosting plant yields and improving fresh marketable weight.

Original article

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Keywords: Control system, LED, leaf senescence, photo-morphology, photosynthetic rate, yield

Introduction

The primary global problems of the twenty-first century are food, resources, the environment, and the quality of life. Human activities, which also result in soil compaction, soil salinization, heavy metal toxicity, extreme pollution, and desertification, are causing the natural environment to deteriorate (Mutombo Arcel et al. 2021). Moreover, climate change's increased complexity associated with agricultural production has made ~~producing~~ predictable and consistent yields more difficult (Newcombe & Nichols 1979). With the help of closed-environment methods like plant factories, vegetables can be effectively cultivated under challenging conditions. Plant factories can grow high-yield, high-quality plants with less water, fertilizer, land, and labor than conventional agriculture. Plant factories are a developing industry with the potential to address some of these conundrums (Hu et al. 2014; Kozai 2013). To implement highly precise control of environmental parameters in the facility, the plant factory integrates contemporary industry, biotechnology, nutrient solution cultivation, and information technology (Kozai et al. 2019). These might be necessary for a plant to grow entirely or partially without being affected by its environment (Mitchell 2012). Regarding the latter, it alludes to the so-called "plant factories" that employ solar lighting to help producers produce large yields.

Light is one of the most critical environmental factor~~s~~ affecting plant growth and development (Buddendorf-Joosten & Woltering 1994). It is an important energy source for plant photosynthesis; ~~it~~ affects morphogenesis and material metabolism (Elmardy et al. 2021; Liang et al. 2021). It is challenging to control natural light due to geographical location, meteorological conditions, and other factors (Cianconi et al., 2020; Knoop et al., 2020). Hence, it is not an ideal light source for studying plant light regulation and plant growth regulation (Kami et al. 2010). LED (light-emitting diode) has the advantages of low heat generation, long service life, good spectral performance, and easy control (Amoozgar et al. 2017; Ferreira et al. 2017). Recently, it has become the predominant source of artificial plant lighting (Dutta Gupta & Agarwal 2017). With the advent of plant factories, three-dimensional spatial cultivation has replaced the traditional single-layer cultivation practiced in fields (Kozai 2012). This process has the superior advantage of inducing a significant change in plant growth, especially in closed plant factories (Saito et al. 2010), while significantly increasing the area under cultivation of plants and reducing the shortage of farmland resources. Furthermore, artificial light sources are used to provide a bright background for plant growth and development (Dutta Gupta & Agarwal 2017).

However, the light absorption area of a plant may change continuously due to the growth of the plant and its cultivation position (Proietti et al. 2021). There may be noticeable light differences in various parts of the cultivation area due to the light properties of artificial light sources. However, conventional plant lighting system uses fixed artificial light source positions and irradiation areas (Dutta Gupta & Agarwal 2017). Therefore, research into a light control device and its control system based on the illuminance distribution properties of artificial light sources, which can dynamically adjust the lighting conditions of the plant's light absorption area in real-time, is essential (Carvalho & Folta 2014).

Although uniform illumination is desirable, optimum energy consumption is a significant factor in designing LED light sources (Wu & Gao 2018). The development of intelligent machine vision for precise irrigation and LED lighting systems has been successful, demonstrating effectiveness in accurately regulating plant moisture content and light intensity

(Hendrawan et al. 2014). Also, in large-scale plantations, these systems can optimize plant growth and reduce water consumption and energy costs. However, light regulation remains a significant issue in large-scale plantations (high plant density) due to occlusion caused by adjacent plant leaves. The occlusion makes it difficult for the middle and lower leaves to receive adequate light compared to the upper leaves (Terashima et al. 2005). The leaf area affects photosynthesis and plant growth by controlling light absorption through the leaf surface, morphology, and orientation (Proietti et al. 2021; Yang et al. 2022). For instance, tomatoes treated with red LEDs caused the tomato leaves to curl upward or downward. However, anomalies in the leaf morphology of the tomatoes were reduced, and the plant biomass peaked when treated with red and blue LED (Fukuda et al. 2008).

Moreover, the abaxial side of the epidermal cells in geranium elongated in response to directional blue light irradiation in a red-light environment, which inhibited the growth of new leaves (Ouzounis et al. 2016). In related studies, it was documented that irradiation of a leaf's adaxial and abaxial sides can increase photosynthesis (Soares et al. 2008; Terashima 1986), and different light colors have different effects on leaf senescence (Causin et al. 2006). Lettuce growth, quality, and light optimization in plant factories have been the subject of numerous studies (Joshi et al. 2017). However, no studies have been conducted to investigate an ingenious way to boost lettuce yields and quality in a plant factory by incorporating movable downward lighting with adjustable sideward lighting. As such, a smart system was developed to help farmers boost lettuce yields and quality in a plant factory by combining movable downward lighting with a supplemental adjustable sideward lighting system. The system's advantages were assessed by looking at the lighting's electricity consumption, plant growth, plant physiology, and the impact of the C-S on leaf senescence.

This research aimed to develop a smart plant factory that could increase lettuce yields and quality while delaying senescence, providing high-quality light but maintaining low output intensity.

Materials and Methods

Design of Plant Light Source Regulation Experiment

Overall design of mechanical structures

The primary design function of the plant light control device is as follows: 1) Adjust the distance of the plant light source and the plant height in a better illumination region. 2) To realize the detection of plant cultivation location. 3) Complete plant growth height detection. 4) Turn on the supplemental sideward plant light source and adjust the angle for a better illumination region. 5) Adjust the lighting area of the light source so that the plant cultivation position is in the optimal light region. 6) Light quality and intensity can be adjusted to meet the plant growth needs at all stages. 7) Human-computer interaction.

The above design requirements, (1), (2), and (5) three points need to be realized by mechanical structure and control system, (3), (4), (6), and (7) can be done by the control system. Taking the light control device design of the ONE-layer plant as an example, its overall structure is shown in Figure 1, and the build experimental plant factory is shown in Figure 5.

System function analysis

In this study, the system's main functions were divided into four functional modules: a collection of information, decision analysis, instruction execution, and human-computer interaction, as shown in Figure 2. According to the plant light control device's design requirements, the control system's functions were decomposed as follows: The information collection function module includes information about plants' growing positions, the height of plant growth, and the working state. The decision analysis function module assesses the various light areas, the calculation of additional light, and the repositioning of the light source. The human-machine interaction functions module, which displays the system's operating parameters and provides an early warning of the system's operational status, is defined by the system's operating parameters. This function module executes instructions, including adjusting the installation's lighting area, lighting ratio, and light source height.

Side ward's LEDs control method

The system is controlled by a human-computer interface, which uses infrared sensors to gather distance data from the plant factory and a lighting sensor to measure ambient lighting. Next, it determines the distance between the cultivation plate and the LEDs and the best PWM for the environmental PPFD using the target PPFD. In this instance, the PWM signal managed the PPFD. As a result, after passing through the power adjustment module, which converts the PWM signal to DC power, the system generates the optimal level of the PWM signal while taking into account the distance between the center LED and the surrounding PPFD, as shown in Figure 3.

System overall scheme design

The detection module consists of two parts: the installation position detection module and the installation height detection module. The execution module consists of the sensor position adjustment module, the light source height module, and the light module, as shown in Figure 4.

The power module adopts a multi-voltage output switching power supply to provide power protection for the regular operation of the remaining modules of the control system: the control module adopts the Arduino Mega 2560 as the core controller, and the control system achieves the expected function: the plant position detection module adopts a micro switch to switch, and the matrix switch its responsible to collect plant cultivation position information and sending it to the control module for processing: the plant height detection module was composed of a row of ultrasonic sensor modules, which detects and collects the growth height of plants and sends it to the control module for processing. The adjustment module comprises of a driver, a stepping motor, and a screw mechanism. It adjusts the part of the plant height detection module, and completes the collection of the height information of all plants in the entire cultivation area through progressive scan detection; the light source height adjustment module composes of a driver, a stepping motor and a screw mechanism to adjust the distance between the LED plant light source and the plant, so that the light absorption area of the plant were always in the area with better light quality; the light module were composes of a driving module, white LED dot matrix , which can adjust the lighting area of the plant light source and independently adjust the intensity the plant light source to achieve functions such as adjustable light quality and light intensity; the interactive module is composes of LCD1602 display and setting buttons, which was the communication between the user and the control system Carrier; the early warning module includes an indicator light and a buzzer, which are used to indicate the working status of the system and alarm when the system works abnormally.

Light height adjustment module for plant

An air guide motor's driver and a screw rod structure are part of the light height adjustment module connected to the upper computer controller. Changzhou Longxiang Company's electric linear actuator motor was adopted for adjusting the height of the downward LED lighting sources. A BXTL 150 electric linear actuator motor with a 100mm pushrod stroke, 100kg thrust, and a rated speed of 12 mm s^{-1}. Real-time measurements of the linear actuator motor's telescopic length and corner data are obtained by the incremental Hall encoder inside the push rod. The circuit design changes the distance between the installation and the LED light source to maintain a better range distance between the light source and the plant. The TB6560 stepper motor control board was employed as the drive because it has an automatic half current and can handle the large load and required drive current of the electrochemical stepper drive in this module. It has a high-stability, affordable stepper motor driver with reliability and anti-interference. It is suitable for various industrial control environments by utilizing high-speed optical isolation, over-current protection, and over-temperature protection functions.

Growth conditions

These experiments were conducted in the key Laboratories of Crop Biotechnology, Fujian Agriculture, and Forestry University. The hydroponic seedling cultivation method cultivated roughly 200 butter lettuce seeds in a plastic cultivation box (110 x 235 x 40 mm). The seeds were placed on an open sponge block after adding clean water to ensure that the sponge submerged completely. After the lettuce seeds had sprouted, they were grown in an environment-controlled growth chamber at 20/17 ^{o}C (photoperiod /dark period) for 12 hours with a PPFD of 50 µmol m^{-2} s^{-1} from cool white fluorescent lamps, and the water in the seedling box was changed to the fresh nutrient solution. After every 12 hours, a new nutrient solution was circulated for 15 minutes at a pH of 6.1± 0.1 and an EC of 1.6± 0.1 mS/cm^{-1}. Following 4 weeks of water cultivation, 36 three-leaf seedlings of equal size were chosen for the experiment; 18 were chosen and grown under the C-S (Figure 5), and the remaining lettuce seedlings were grown under the N-S. The cultivation board was constructed from a polyethylene foam board and measured 110 x 50 x 10cm. The deep-flow hydroponics cultivation method was used, and the plant factory strictly controlled several environmental factors during the cultivation period (Causin et al. 2006). The air temperature at night was kept at 20.2°C and 23 °C during the day.

The relative humidity was kept at 60 ± 5%, and the carbon dioxide concentration was kept at 400 ± 10ppm. Because the factories had to be filled with pure CO_2 injected into the interior to ensure environmental controllability, the carbon dioxide concentration was the same as the outside atmosphere. The transplanted seedlings were left in the improved fresh nutrient solution, and the pH value and EC value of the nutrient solution were strictly controlled, where pH=6.5 ± 0.1, EC = 1.7 ± 0.2mS m^{-1}.

Light treatments

As seen in Figure 5, the machine was constructed with a movable downward and flexible sideward lighting system. In total, 6 LED panels were used during the experiment for the two treatments—C-S and N-S—. A group without supplemental light was set as the control (N-S) with all 6 LED panels horizontally above the plant with the intensity of 280μmol m^{-2} s^{-1} at T1 and T2, and there was no change. In the C-S, 4 LED panels were used for the moveable downward lighting system, placed horizontally above the plant with a PPDF of 200μmol m^{-2} s^{-1} at T1 and T2, and 2 LED panels were placed on the side as supplementary adjustable sideward light. After monitoring multi-point averages in each treatment region following the plant growth, the additional adjustable sideward light angle was established. The supplemental adjustable sideward light intensity was controlled by regulating the lamps at 50μmol m^{-2} s^{-1} PPFD at T2 from 8:00 to 24:00. Spectroradiometers were used to identify the spectra of the light sources. A quantum radiation probe (FLA 623 PS, ALMEMO, Holzkirchen, Germany) was utilized to measure the additional light intensity at the top leaf level of the cuttings at night.

It should be noted that the sideward lights were not turned on until 20 days after transplanting, not at T1, when all of the outer leaves had taken on a shade-like appearance. The LEDs used were specially made by Sung K wang LED Co., Ltd. in Incheon, Korea, and they produced a broad spectrum with a clear peak at 420 nm, ranging from 360 to 760 nm (blue). To control the electrical power, current, and PPFD of light sources, a switched-mode power supply was used.

Plant growth and sample processing

Five plants from each replicate were taken from each treatment 20 days (T1) after transplanting and 40 days (T2) after harvest, and their morphology was assessed. Moreover, we also measured the fresh weight (FW) and pigment content of samples of fresh lettuce. The shoot length was measured from the rhizome base to the plant's top using a ruler (cm). The stem diameter was measured using digital calipers (mm), and the fresh and dry mass was weighed using an electronic balance (0.0001 g). The total leaf area (cm^2) (summation of leaf areas) was estimated as described by Pandey and Singh (Pandey & Singh 2011). Fresh shoots and roots were put in paper bags and transferred to an oven at 75 ℃ for at least 48 h to obtain the dry weight.

Photosynthetic pigments content

Chlorophyll content was extracted from the fresh lettuce leaves of both treatments. The fresh leaf tissue (0.2 g) was cut and ground thoroughly and later placed in 5 ml of 95% ethanol and filtered. The volume was then increased to 25 ml using 95% ethanol. A UV-5100B spectrophotometer was used to estimate the absorbance of the extracted solution at 665 nm (OD665), 649 nm (OD649), and 470 nm (OD470) (Unico. Shanghai, China). The chlorophyll content was calculated using the equations below(Cataldo et al. 1975; Knight & Mitchell 1983):

$$\text{Chl } a \text{ (mg g}^{-1}\text{)} = (13.95OD_{665} - 6.88OD_{649})V/200\ W$$

$$\text{Chl } b \text{ (mg g}^{-1}\text{)} = (24.96OD_{649} - 7.32OD_{663})V/200W$$

$$\text{C (mg g}^{-1}\text{)} = (1000OD_{470} - 2.05\text{Chl } a - 114.80\text{Chl } b)\ V/(245 \times 200\ W).$$

Where (Chl*a*) = chlorophyll *a*, (Chl*b*) = chlorophyll *b*, (C) = carotenoid, mg/g; (V) = volume (25 mL), and (W) = sample weight (g).

Biochemical contents

Nitrate content

Small pieces of fresh lettuce weighing 0.6 g each were cut up, placed in a test tube with 10 mL of distilled water, and heated in a water bath to 99 °C for 30 minutes before cooling to 25 °C. 25 mL of the extract was added to distilled water, followed by 0.1 mL of the supernatant and 0.5 mL of 5% (w/v) salicylic acid in concentrated H_2SO_4 combined with (SA-H_2SO_4). After 20 minutes, the sample was cooled at room temperature, and 9.5 mL of 8% NaOH was gradually added to the combined supernatant. The absorption of the nitrogen content in the leaves at 410 nm was measured using the spectrophotometer UV-5100B (Unico, Shanghai, China). The following formula was used to calculate the nitrate content (Muneer et al. 2014).

Nitrate content (mg kg^{-1} FW) = (C × V t)/ (W × Vs)

Where: C=the nitrate value from the standard curve (μg m L^{-1}); Vt=Total samples volume extracted; Vs=Taken sample solution (4 mL); W=Fresh leaf weight (g)

Soluble protein content

The Coomassie brilliant blue G-250 dye method by Muneer, Kim et al.(Muneer et al. 2014)was used to determine the soluble protein content of lettuce. Liquid nitrogen and 5 mL of distilled water were also used to grind 0.5 g of fresh lettuce into pulp. After centrifuging the extract solution at 10000 rpm for 10 minutes at 4 °C, 0.05 mL supernatant was combined with 0.95 mL distilled water and 5 mL Coomassie brilliant blue G-250 solution (Sigma, USA, 0.1 g L^{-1}). After 2 minutes, the absorption was measured at 600 nm using a UV-5100B spectrophotometer (Unico, Shanghai, China).

Soluble sugar content

Fresh leaves were cut into small pieces and weighed (0.2 g) to measure some biochemical compounds of interest. The soluble sugar content was calculated using the anthrone colorimetric method (Weiguo et al. 2012). The absorbance of the extracted solution was measured using a UV-5100B spectrophotometer at 595 nm (OD595) (Unico, Shanghai, China).

Ascorbic acid content and total nitrogen utilization efficiency

RQFlex plus reflectometer (Merck, Darmstadt, Germany) was used to determine the ascorbic acid content of plants in each treatment, according to Tabata, Ôba et al.(Tabata et al. 2001) procedure. The following formula was used to compute nitrogen-utilization efficiency (NUtE)(Siddiqi et al. 1990), with the results reported as g 2DW mg^{-1} N:

NUtE = Total leaves DW/Total nitrogen content (TNC)

Photosynthetic productivity and efficiency

Net photosynthetic rate (*A*), stomatal conductance (gs), leaf transpiration rate (*T*r), and intracellular CO_2 concentration (C*i*) were measured using a portable photosynthesis gas analyzer (LI-6400, LI-COR). These parameters were used as indicators of the plant's gas exchange performance. The outer and inner leaves (fully developed leaves) were randomly sampled from each plant's top. Each replicate contained 4 leaves from 4 different plants (16 replicates). The leaf temperature, CO_2 concentration, and relative humidity (RH) were set at 25 °C, 400 µmol mol^{-1}, and 70%, respectively.

Electricity consumption measurements

Utilizing an electricity meter (LCBG-ZJ341-07; Li Chuang Science and Technology Co., Lai wu, China), the illumination's electricity consumption was calculated (the energy costs for cooling, ventilation and the recirculation of the nutrient solution were not considered during our experiments). It determined how much light each treatment used [LUE (grams per kilowatt hour)] [LUE = leaf FW (grams per plant) 18 plants/m^2/electric-energy consumption of illumination (kilowatts per hour)].

Statistical analysis

Data were analyzed using the software"Statistics 8.1" (Gomez & Gomez 1984; Sánchez-Rodríguez et al. 2010). The t-test was used to find significant differences among treatments, and four replicates were considered for the experiment. The significant differences between treatments were compared by the least significant difference LSD ($p \leq 0.05$)(DADKHAH et al. 2009).

Results

Plant Growth

After cultivating the plants under the N-S and the C-S in the plant factory over 40 days after transplanting, we observed distinct variations among the various parameters assessed. For instance, the C-S treatment had a significant impact on the morphology of lettuce plants, including the length of the shoots (Figure 6 A), the diameter of the stems (Figure 6 B), and the number of leaves (Figure 6 D). When the supplement adjustable sideward lighting LEDs were turned on and used in conjunction with the movable downward lighting LED system, root fresh weight between N-S and C-S after 20 days of sowing was not significantly different (Figure 6 G). However, the leaf area, root length, shoot fresh weight, shoot dry weight, root dry weight, and dry weight content under C-S were significantly higher than N-S at T2, as shown in figures 6 C, E, F, H, I, and J, respectively.

The plants treated under the C-S and the N-S had very different morphologies; plants subjected to the C-S appeared dense, with narrow, twisted leaves, and no excessive elongation was observed. On the other hand, plants under the N-S were short with hypertrophic and thick leaves and a yellowing color, despite the daily consumption of vital and electric energy and had the sparsest plant architecture with a noticeable elongation of the stem. This implies that the optimal wavelength for plants should be adjusted following plant growth and that the C-S exhibited superior performance.

Photosynthetic pigments content and biochemical contents

The supplementary sideward light source significantly impacted the levels of chlorophyll *a* and *b*, soluble sugar, and soluble proteins. The lettuce grown under C-S at T2 had the highest chlorophyll *a* and *b* concentrations (Figure 8 A and B). It was observed that chlorophyll *a* concentration under N-S at T1 was the lowest compared with C-S at T2. At T 2 Compared to plants cultivated under N-S, lettuce's carotenoid concentration dropped under C-S largely due to the additional sidelight. This indicates that time directly affects how carotenoids are transformed into pigment in plants, as shown in Figure 8C. The supplemental lights helped to increase the amount of soluble sugar in the lettuce leaves, with C-S at T2 yielding the highest level compared with N-S (Figure 8 F). The N-S-treated lettuce had the lowest soluble protein levels at T1, but these levels somewhat increased at T2 relative to those under C-S. The highest soluble protein levels were found at T2 under C-Scompared with N-S(Figure 8 E). However, nitrate content exhibited no discernible variations between the two treatments(Figure 8 D).

Ascorbic acid content and total nitrogen utilization efficiency

The ascorbic acid concentrations in plants under the N-S treatment did not vary significantly compared with those under the C-S treatment. The outer leaf generally had a higher ascorbic acid level than the inner and total leaf (Figure 9). Total nitrogen utilization efficiency in plants under the C-S was higher than that under N-S at both T1 and T2 (Figure 10).

Photosynthetic productivity:

The C-S treatment influenced the photosynthetic rate, stomatal conductance, evaporation rate, and CO2 concentration in the newest fully developed leaves with the additional adjustable sideward lighting at a PPFD of 50 µmol m^{-2} s^{-1} compared with the N-Streatment. The lowest rate of evaporation was seen in the control group. The stomatal conductance showed similar patterns. Under the C-S, which was about twice that of the control, the stomatal conductance peaked significantly. The leaves showed positive net photosynthetic rates (Table 2). These findings showed that leaves' ability to increase photosynthesis might be regulated by additional, adjustable side lighting

Light and Energy Use Efficiency

The segmented energy consumption of the C-S and N-C is shown in Table 3. C-S began to increase on day 20, while N-S continued to outperform in terms of energy consumption until the harvesting period. The power consumption per unit area, the output per unit area, and the power utilization efficiency (LUEs) of the C-S and the N-S were measured and calculated separately (Table 4). The comparison showed that the power consumption of the C-S was 35.02% lower than that of the N-S. We pointed out that the power utilization rate of LUEs was a practical value for comparing the power utilization rate between the systems. Therefore, it was observed that at relatively low output, the power utilization rate of the C-S was 135% higher than that of the N-S. It is indicated that C-S can allow the lettuce to receive the ideal light under the conditions of large-scale plantations in plant factories, obtain relatively more biomass and consume the least energy value.

Discussion

Response of the morphology and photosynthetic pigment under different irradiances

Plants' morphology is changeable, and they have developed mechanisms to adapt to various environments (Kumar et al. 2018; Li et al. 2021). Research demonstrated that lighting quality, intensity, source, and photoperiod affect plant morphology. However, only a few studies have looked at how the orientation of the light source affects the development and growth of plants. It has been demonstrated that lettuce grows more efficiently under a combination of downward and upward lighting settings (Joshi et al. 2017). Also, high light levels boost photosynthesis and subsequently increase plant biomass, whereas low light intensities typically result in photoinhibition and impact plant photomorphogenesis (Chen et al. 2016; Kelly et al. 2020). Woltering and Witkowska showed that higher PPFD increased the dry matter content of lettuce, indicating higher carbohydrate levels and improved post-harvest quality (Woltering & Witkowska 2016). Here, we observed that C-S significantly outperformed N-S in terms of above-ground and root biomass (fresh weight and dry weight), dry matter content, and leaf weight of lettuce while significantly delaying the senescence of outer leaves in plants, leading to a higher photosynthetic activity. These results aligned with recent studies, implying that plant shoots' fresh weight/dry weight is influenced by both plant morphology and photosynthetic capacity (Hernández et al. 2016; Wang et al. 2016). However, tip burn was observed among lettuce plants cultivated indoors under the increased light intensity. Correspondingly, Sago noted that butterhead lettuce frequently experienced tip burn when exposed to high light intensities (150 and 300μmolm^{-2}s^{-1}), which may have been induced by a calcium deficit in the interior leaves(Sago 2016). The lettuce cultivar used in the current study were grown in C-S and N-S treatments with higher PPFD of 200+50 and 280μmolm^{-2}s^{-1}, respectively. Neither cultivar displayed the tip burn phenomenon, proving that these PPFD were not excessive for lettuce growth.

Plants rely heavily on chlorophylls (Chl) for photosynthetic capacity and growth (Factors Influencing Leaf Chlorophyll Concentration in Natural)(Li et al. 2018), and the chlorophyll content of vegetables is also significant for the visual appearance of the vegetable. A consumer will accept or reject a product based on its color and appearance, and these qualities are even more important in a product, such as microgreens, which are highly valued for the colors they include (Barrett et al. 2010). Chlorophyll levels can be influenced by both the intensity of the illumination and the plant's genotype, as has been described in the literature(Teng et al., 2021). In lettuce treated with 250 $\mu molm^{-2}s^{-1}$, it was evident that higher light intensities were easily accessible to higher chlorophyll *a*/*b* levels. In contrast, the concentration of chlorophyll *a* and *b* decreased by 300 $\mu molm^{-2}s^{-1}$. Likewise, the use of 200$\mu molm^{-2}s^{-1}$+ 50$\mu molm^{-2}s^{-1}$ under C-S at T2 was beneficial for the accumulation of chlorophyll a and b (Figure 8 A and B), and this enhancement was discovered to be directly associated with the development of the leaf structures.

The senescence of the leaves is a fundamental attribute that decreases the post-harvest performance and the nutritional content of horticultural crops, the yield of agricultural crops, and the buildup of biomass. Senescence also restricts the production of agricultural crops(Guo & Gan 2014). Senescence can be prolonged by a lack of light (Bresson et al. 2018; Guo & Gan 2014). Light regulation remains a major issue in large-scale plantations (high plant density) due to occlusion caused by adjacent plant leaves, making it difficult for the middle and lower leaves to receive adequate light compared to the upper leaves(CHAPEPA et al. 2020). This pattern was observed in this study, with lettuce grown in the N-S treatment tent being yellow at T2. This must be the result of unbalanced radiation on the cultivar plate, which accelerates the senescence of leaves.

In contrast, lettuce grown in the C-S treatment tent at T2 displayed a very good green hue. The senescence of leaves due to low light levels is accompanied by the transfer of nutrients to younger tissues, the loss of chlorophyll, the breakdown of photosynthetic proteins, and a decrease in photosynthetic activity (Thimann & Satler 1979; Wingler et al. 2006). These findings demonstrated that the sideward and upward combination might delay the middle leaf's senescence in plant factories. That was consistent with the conclusions of lettuce grown under Supplemental lighting (Joshi et al. 2017; Zhang et al. 2015). This result explains the increment in marketable leaves, as shown in Figure 11A.

Response of soluble protein, nitrate, and soluble sugar under different irradiances

An accumulation of soluble carbohydrates could result from more intense lighting (Bian et al. 2015). The soluble protein plays a vital role in the osmotic regulation and metabolism of several metabolic enzymes. Plant resistance and metabolism are embodied in soluble protein content. As a result of the synergistic effect of the C-S lighting's improved stomatal characteristics, photosynthetic pigment concentrations, and use efficiency of light delivered in diverse directions, our data showed that the soluble protein levels were increased under C-S lighting (Figure 8F).

Nitrates are one of the most important molecules in determining the nutritional value of food. Nitrate (NO_3^-) can accumulate to varying degrees in vegetables and may cause human health issues (Kim et al. 2006). Romaine lettuce is a strong provider of nutrients and has low NO_3^-. Many factors, including light levels, contribute to the final nitrate content in plants (Lillo & plants, 2004). The light intensity and quality affect nitrate uptake, translocation, and decrease in plant organs. Romaine lettuce grown under light-emitting diodes with changing the light conditions during growth had lower levels of nitrate(Nicole et al. 2018).

Consequently, children can eat romaine lettuce as part of a balanced diet without the risk of methemoglobinemia or other adverse effects. Our results showed that nitrate concentrations were higher under C-S than N-S at T2, with a substantial impact from the substrate component. For instance, nitrate levels in coconut fiber dropped dramatically due to exposure to supplemental light. Lettuce is confirmed as a nitrate accumulator (Jannat et al., 2022). If growers aim for fruit and vegetables with a high concentration of beneficial chemicals and a low nitrate content, then the C-S combined with LED lighting may be the way to go (Figure 8D).

As soluble sugars are highly sensitive to environmental stresses, they act on the supply of carbohydrates from source organs to sink organs. Besides regulating lettuce biomass and morphology, light intensity also impacts nutrition quality and anti-oxidative enzyme activities (Fan et al., 2013; Weiguo et al., 2012). Light intensity increases lettuce's soluble sugar and ascorbic acid content (Zhou et al., 2011). Furthermore, the different lighting conditions that exist throughout the growing cycle have the potential to influence the total amount of carbohydrates present in the plant. These variables can stimulate photosynthetic activity (Cocetta et al., 2017). It was discovered that the amount of soluble sugar in strawberries rose in proportion to the direction of the irradiance when the top and side illumination were utilized (Yang et al., 2021; Yang et al., 2022). There was an increase in the levels of expression of genes involved in sugar metabolism and signaling in lettuce cultivated with supplemental lighting（Viršil et al., 2020). Vegetables' sucrose concentration and nutritional profile can be improved with the help of a special LED light, as revealed by Lin et al. (Lin et al., 2013). These results were consistent with prior research, indicating that the principal lighting direction can enhance the concentration of primary metabolites(Yang et al., 2021; Yang et al., 2022).

Response of ascorbic acid under different irradiances

Vitamin C, also known as ascorbic acid, is found in high concentrations in plant foods. It is present in all cell compartments, including the cell wall, and reaches a concentration of more than 20 mM in the chloroplasts where it is found(Gallie 2013; Smirnoff & Wheeler 2000). Multiple reports indicate light enhances vitamin C concentration in plants (Li et al., 2010; Massot et al., 2012). The varied light irradiance impacted ascorbic acid in romaine lettuce in the C-S and N-S. (Figure 9). The ascorbic acid content of plants growing under C-S was higher at T2 than at T1. Although there is no reason for such an increase, sideward irradiance on leaves may help producers achieve their goals if they want their ascorbic acid levels to increase. As a consequence, it is crystal evident that it is possible to coordinate the factory's light source with the production targets that need to be met. Similar results have been seen for ascorbic acid, alpha-carotene, and phenolic compound levels when treated with UV light (Xie et al., 2014) or red light (Samuolienė et al., 2010) during the latter stages of culture.

Response of stomata under different irradiances

The opening and closing of guard cells control the quantity of stomata, which carry air and water vapor during carbon assimilation, respiration, and transpiration. Light, temperature, and CO_2 are exogenous factors influencing the stomata's opening and closing. In our study, romaine lettuce plants cultivated under C-S lighting had the highest stomata density, whereas plants grown under N-S lighting had fewer stomata. Notably, the supplemental sideward lighting enhanced the stomatal opening but not the N-S lighting. Thus, romaine lettuce plants grown under C-S lighting appear to have higher photosynthetic efficiency due to favorable stomatal conditions. (Kardel et al., 2010; Moore et al., 2021). This led to the highest biomass production rates, plant growth, and development. This result was in accordance with a study that demonstrated side lighting could promote stomatal formation (Yang et al., 2021).

Electric-energy consumption of the lighting systems

Optimizing the plant factories' performance across their energy spectrum is crucial for ensuring the design's long-term viability. Lighting fixture position influences cultivation productivity and system lighting efficiency; according to Massa et al. (Massa et al., 2007), the inverse square law, the PPF decreases as the height of the lighting fixture increases. LED lighting systems can be positioned closer to the crop tissues due to the heat being evacuated from the lighting-emitting surface by properly constructed heat sinks. The installation, placement, and distribution of lighting designed for the morphology of the crops by taking into consideration their height, size, and shape are crucial for improving the profitability and sustainability of indoor cultivation if the use of reflective surfaces enables light photons to reflect toward the canvas (Gomez et al., 2013). LED panels with different illumination schedules and mounted above butterhead lettuce (Lactuca sativa capitata) seedlings were examined. The highest light efficiencies and lowest electricity consumption were found for the treatments with irradiation from a shorter distance above the seedlings(Li et al. 2014). In this study, the test variety was romaine lettuce, the ordinary system N-S was the control group, and the C-S lighting system was the experimental group. The experimental group's (C-S) energy usage fell by 35,02%, and the power utilization rate increased by 135 %. The lighting system built in this study has energy-saving properties and a high energy utilization rate in the seedling stage of plant growth. The lighting design of C-S can provide the light requirements for later plant growth. This outcome is consistent with Casciani et al. research which found that reducing fixture spacing and focusing lights at the canopy will minimize lighting pollution and energy consumption (Cocetta et al., 2017), and lightning-quick efficiency.

Conclusions

The results of our study clearly show that the two systems had different effects on lettuce culture in the plant factory at times T1 and T2 under different lighting irradiance. In a plant factory, light control devices are equipment foundations to realize light environmental precision control for plant growth and enhance plant production efficiency. The new lighting type systems have successfully reduced the quantity of light energy consumption in the plant factory, boosted lettuce yields and quality, slowed the decrease of chlorophylls, and prevented premature aging and falling of lower leaves. We have concluded that using C-S lighting systems in plant factories that use artificial lighting will result in significant benefits. C-S lighting can increase plant output through a correct light source configuration and make the plant factory system applicable to many plants. Still, more research is required about the onset of supplemental sideward and adjustment changes in response to different lighting directions.

Acknowledgments

This work was financially supported by the Nature Science Foundation of Fujian Province of China .

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Figure 1

The overall structure of the light control device

The primary design function of the plant light control device is as follows: 1) Adjust the distance of the plant light source, and the plant height in a better illumination region. 2) To realize the detection of plant cultivation location. 3) Complete plant growth height detection. 4) Turn on the supplemental sideward plant light source and adjust the angle for a better illumination region. 5) Adjusting the lighting area of the light sourceso that the plant cultivation position is in the optimal light region. 6) The light quality, light intensity can be adjusted to meet the plant growth needs at all stages. 7) Human-computer interaction. The above design requirements, (1), (2), and (5) three points need to be realized by mechanical structure and control system, (3), (4), (6), and (7) can be done by the control system. Taking the light control device design of the ONE-layer plant as an example, its overall structure is shown in Figure 1, and the build experimental plant factory is shown in Figure5.

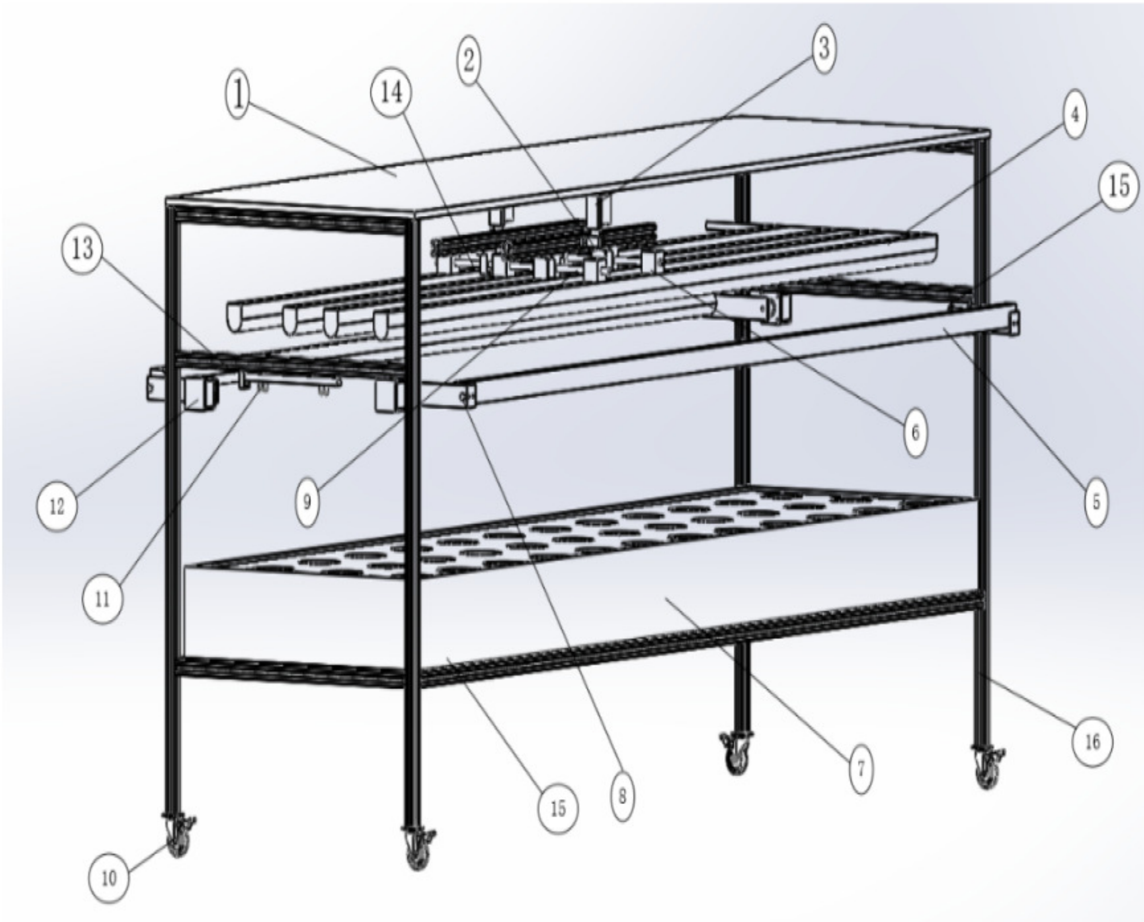
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Figure 2

System function breakdown diagram

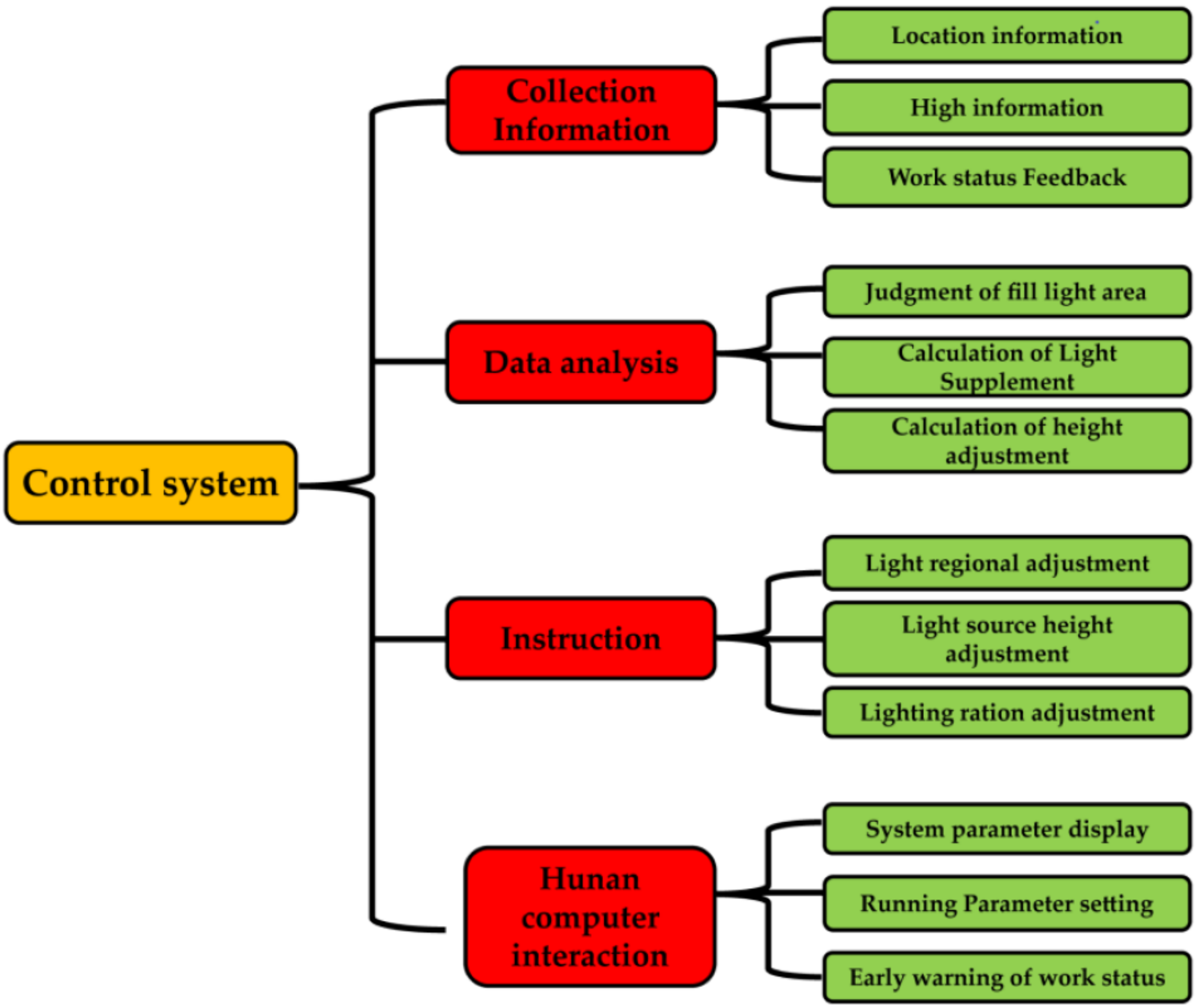

Figure 3

The system runs from human-computer interaction

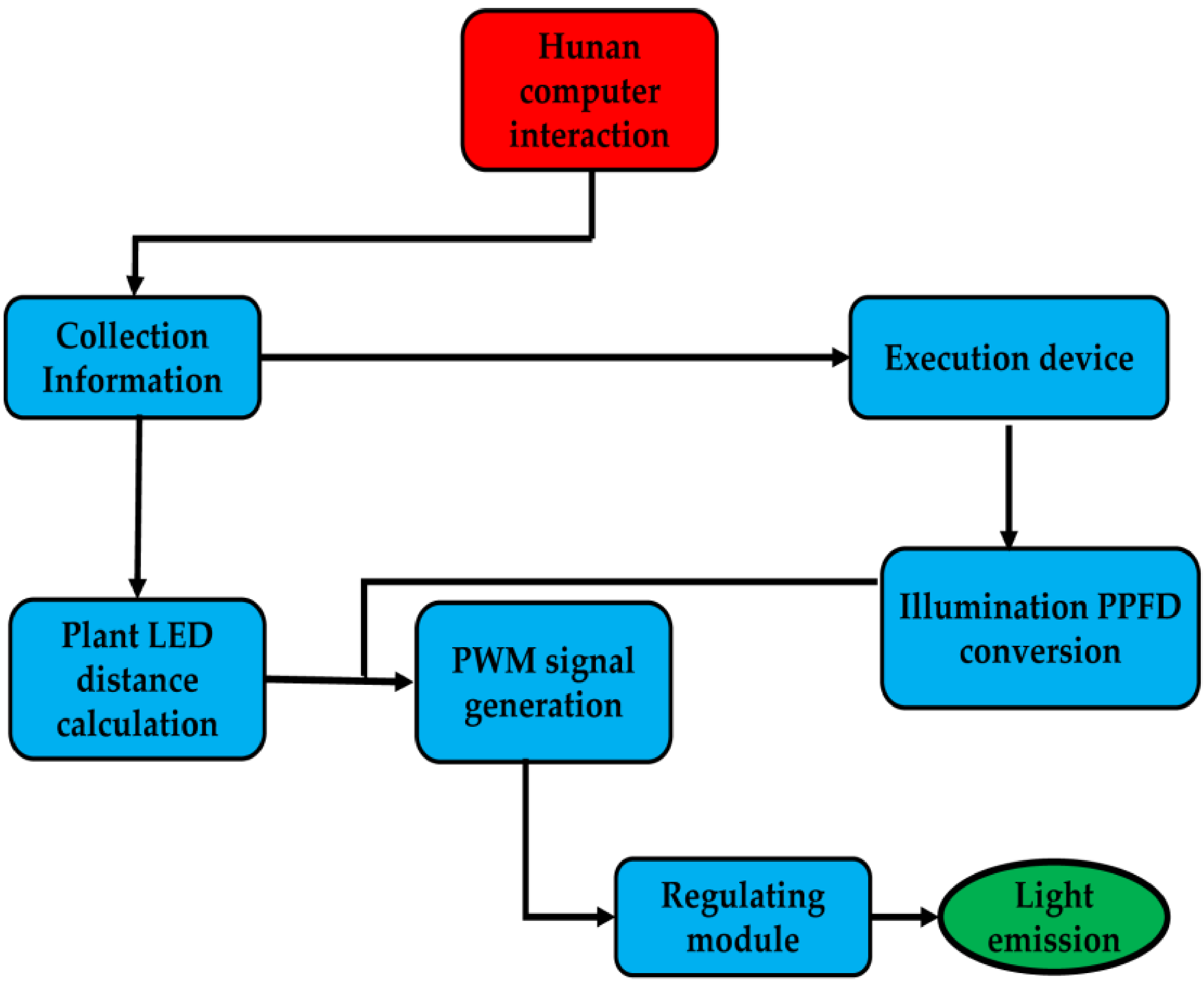

Figure 4

The overall structure of the system

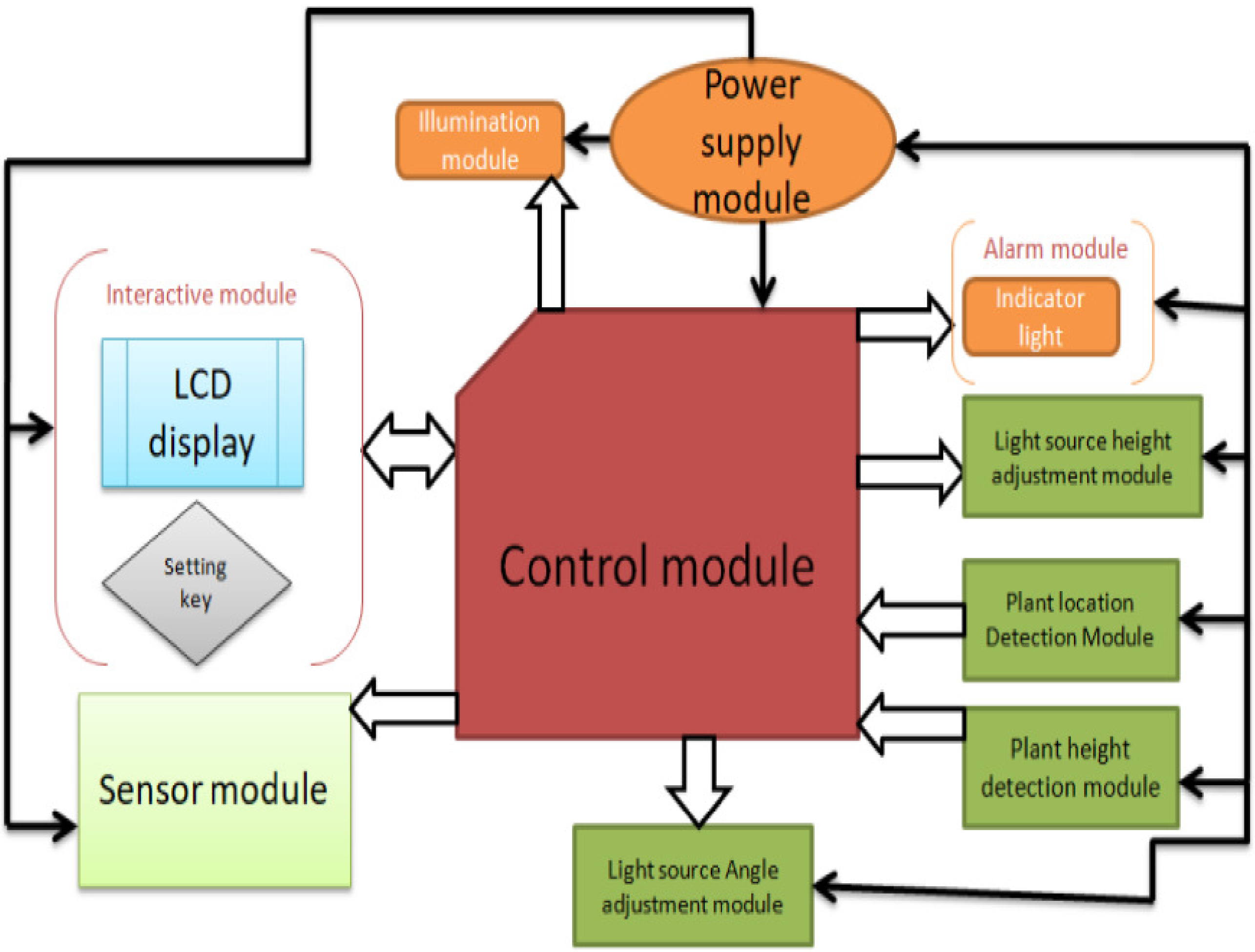

Figure 5

The combination of the movable downward lighting and supplemental adjustable sideward LED lighting

Figure 6

Effects of different illumination systems

Effects of different illumination systems on Shoot length (A), Stem diameter (B), Leaf area (C), No. of leaves (D), Root length (E), Shoot fresh weight (F), Root fresh weight (G), Shoot dry weight (H), Root dry weight (I), and Dry weight content (J). Values are means of four technical replicates (n=5) ± standard error; *= is significant at $p \leq 0.05$ level; **= is significant at $p \leq 0.01$ level for each time between treatments according to the T-test.

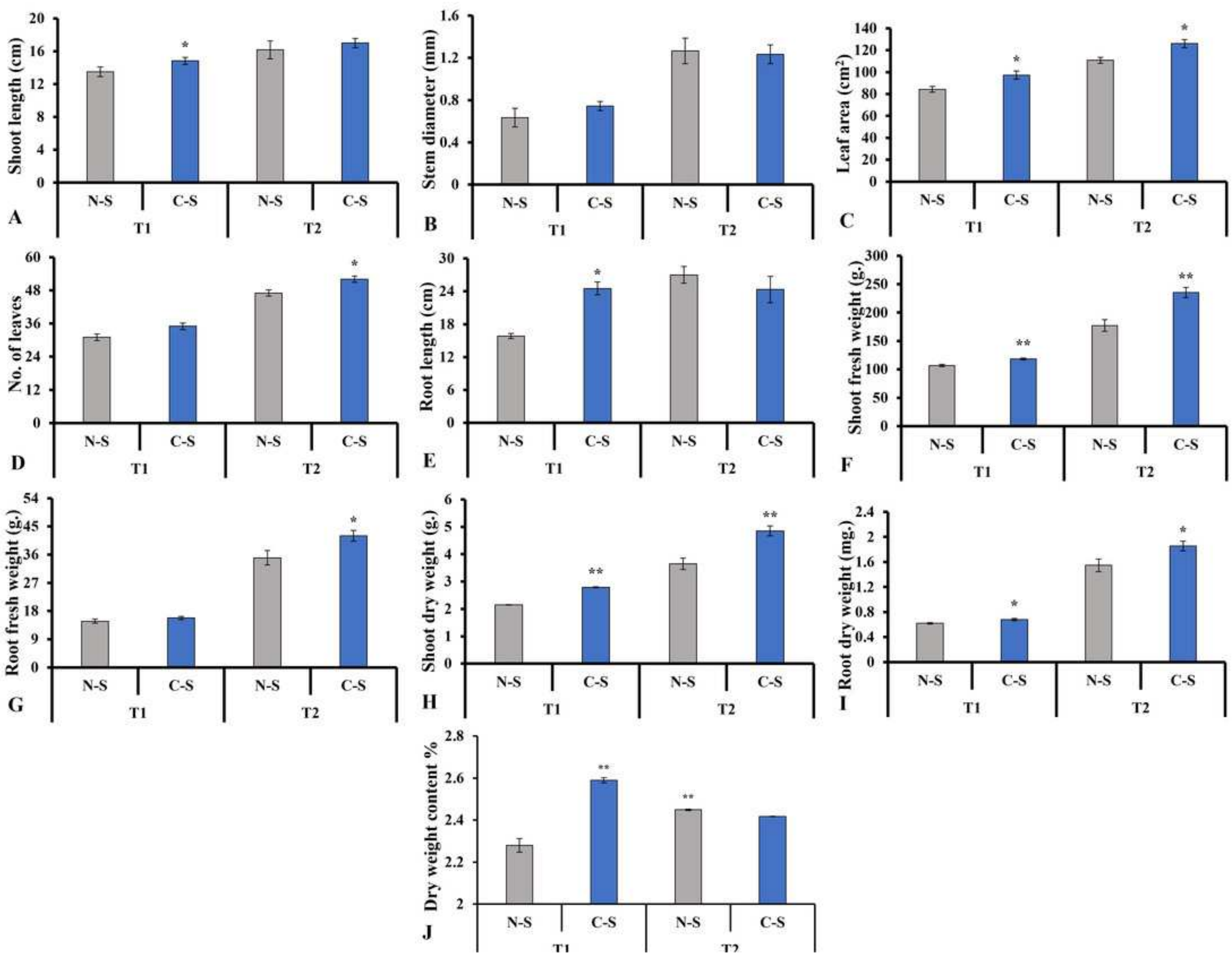

Figure 7

Morphology

Morphology [N-S at T1 (a), C-S at T1 (b), N-S at T2(c), and C-S at T2 (d)] of lettuce (at harvest) planted in varied light treatments.


5 cm
5 cm
5 cm
5
cm
5 cm
5 cm
5 cm
5 cm

Figure 8

Effect of different illumination systems on the photosynthetic pigments content and biochemical contents

[Chlorophyll *a* (A), Chlorophyll *b* (B), Carotenoid (C), Nitrate content (D), Content of soluble protein (E), Content of soluble sugar (F)]. Values are means of four technical replicates (n=5) ± standard error; *= is significant at $p \leq 0.05$ level; **= is significant at $p \leq 0.01$ level for each time between treatments according to the T-test.

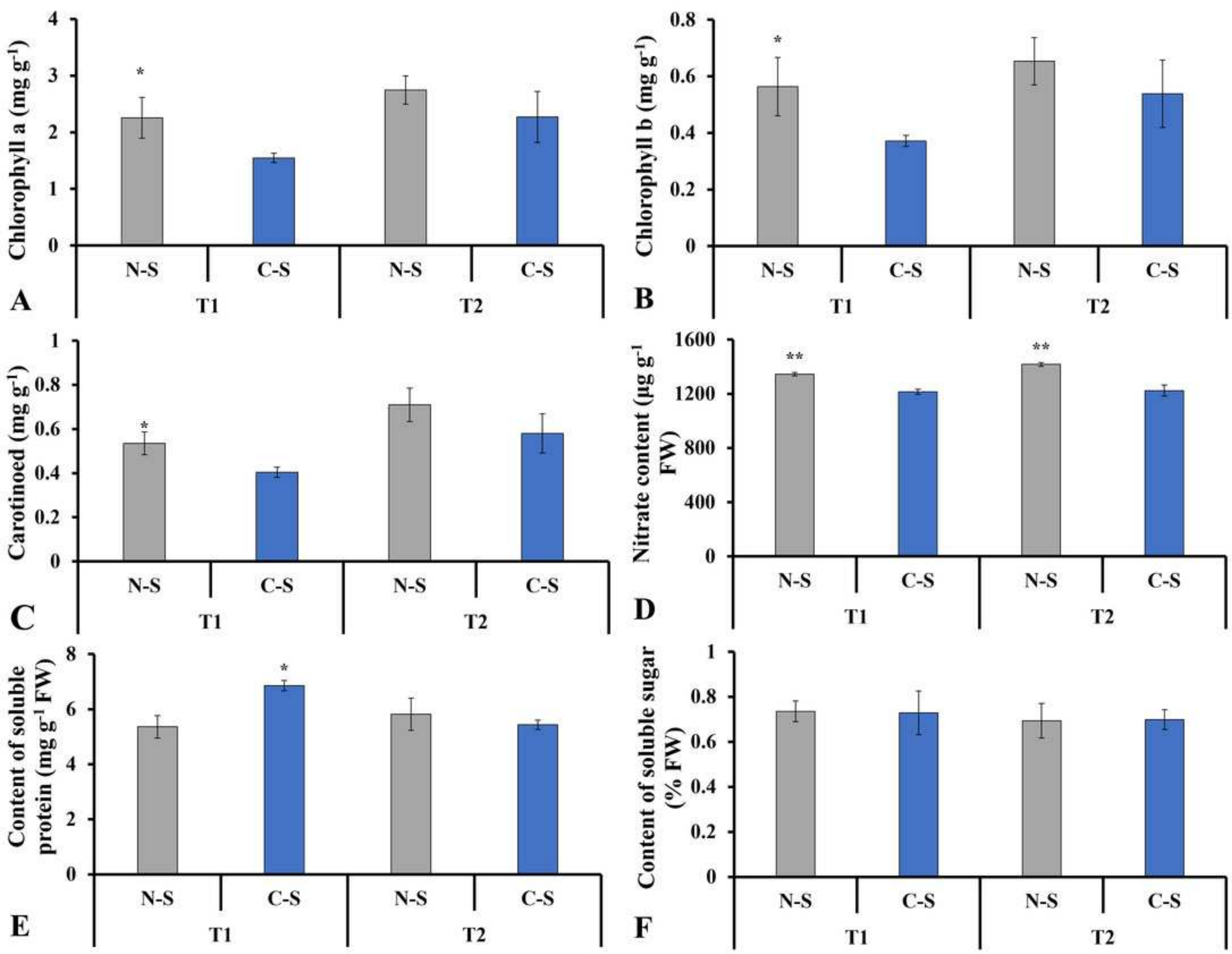

Figure 9

Ascorbic acid content

Ascorbic acid content at 40 days after transplanting in the outer leaves, inner leaves, and total leaves of lettuce plants grown under N-S and C-S. Values are means of four technical replicates (n=5) ± standard error; *= is significant at $p \leq 0.05$ level; **= is significant at $p \leq 0.01$ level for each time between treatments according to the T-test.

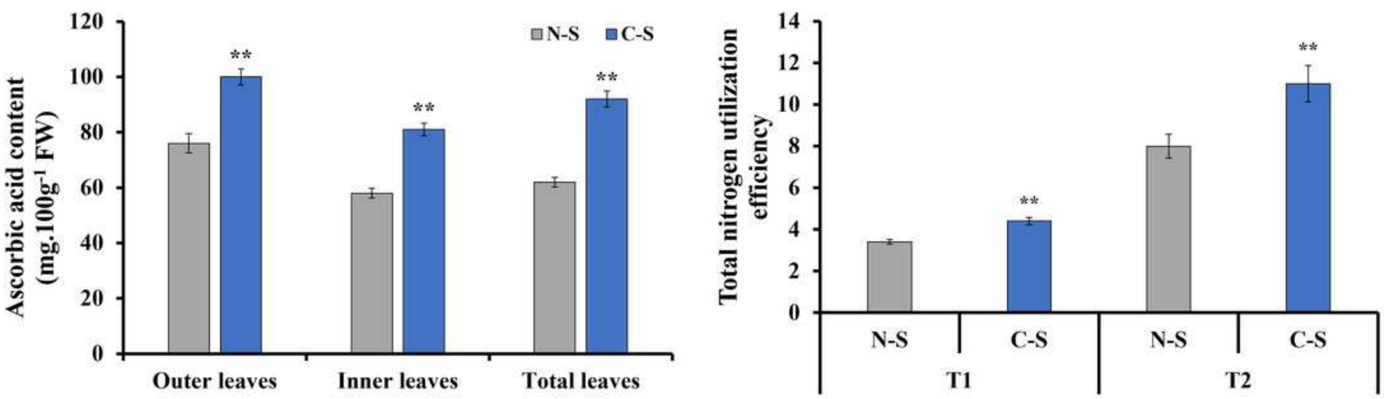

Figure 10

Total nitrogen utilization efficiency

Total nitrogen utilization efficiency cultivated under N-S and C-S at T1 and T2 after transplanting. Values are means of four technical replicates (n=5) ± standard error; = is significant at p ≤ 0.05 level; = is significant

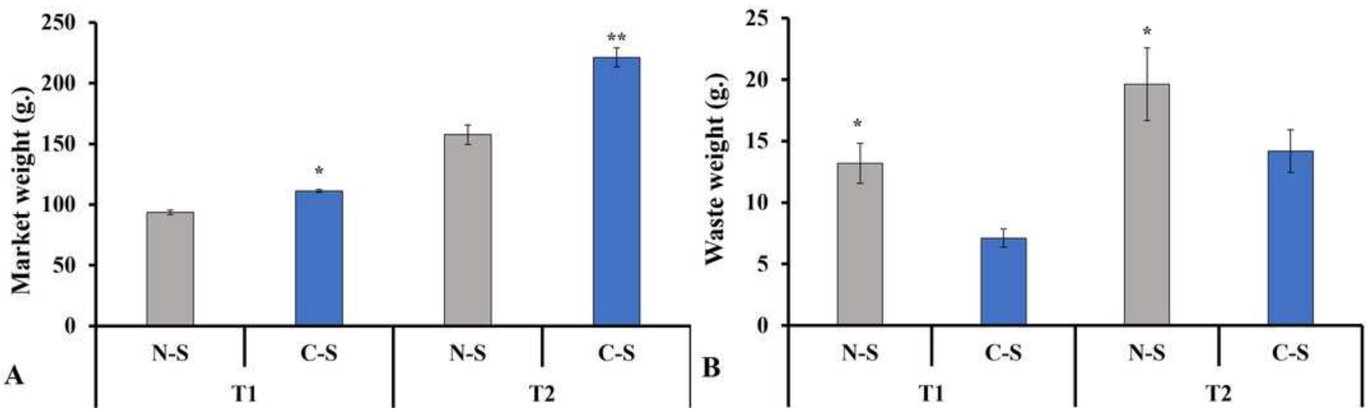

Figure 11

Figure 11.Total marketable leaves

Total marketable leaves fresh weights (A) and waste leaves (B) from plants cultivated under N-S and C-S at T1 and T2 after transplanting. Values are means of four technical replicates (n=5) ± standard error; = is significant

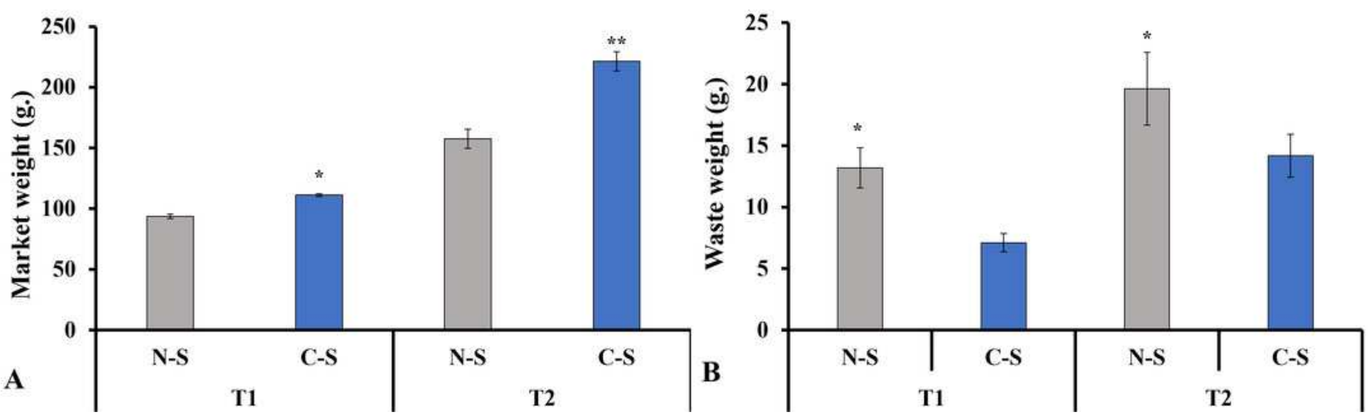

Table 1(on next page)

Lighting parameters number of the LED source panel

D+S (downward +supplemental sideward lighting)T1(1days transplanting to 20after transplanting),T2 (20-40 days after transplanting)

Table 1 Lighting parameters/number of the LED source panel D+S (downward +supplemental sideward lighting)

T1(1days transplanting to 20after transplanting),T2 (20-40 days after transplanting)

Parameter(s)		(C-S)	(N-S)
Lighting source (LED panels)	T1=(D+S)	4+0	6+0
	T2=(D+S)	4+2	6+0
Light intensity(μmol m^{-2} s^{-1})	T1=(D+S)	200+0	280+0
	T2=(D+S)	200+50	280+0
Spectrum(nm)		360 to 760	360 to 760
Time(h)		8:00 to 24:00	8:00 to 24:00

Table 2(on next page)

Effects of different illumination systems on net photosynthetic rate (*A*), stomatal conductance (g_s), leaf transpiration rate (*T*r), and intracellular CO_2 concentration (C_i)

Table 2. Effects of different illumination systems on net photosynthetic rate (*A*), stomatal conductance (g_s), leaf transpiration rate (*T*r), and intracellular CO_2 concentration (C_i)

Photosynthetic parameters	The experimental group (C-S)	Controlgroup experiment (N-S)
Net photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	6.50±0.34a	5.72±0.38b
Stomatal conductance (mol H_2O m^{-2} s^{-1})	0.09± 0.10a	0.05±021b
Evaporation rate (μmol H_2O m^{-2} s^{-1})	0.53±0.07a	0.37±0.11b
CO_2 concentration (μmol CO_2 mol^{-1})	305.10±24.54a	282.43±12.63b

Table 3(on next page)

Segmented energy consumption of different lighting systems

Table 3. Segmented energy consumption of different lighting systems

Segmented energy consumption (kWh)	(C-S)	(N-S)
1-5days	6.5	9.8
5-10 days	13	19.6
10-15 days	19.5	29.4
15-20days	26	39.2
20-25days	32.15	49
25-30days	39	58.8
30-35days	44.8	68.6
35-40days	52.25	80.41

Table 4(on next page)

Effects of different illumination systems on electricity consumption, plant yields, and efficiency LEDs

Table 4. Effects of different illumination systems on electricity consumption, plant yields, and efficiency LEDs

Growth parameter(s)	(C-S)	(N-S)
E-consumption (Kw h m^{-2})	52.25	80.41
Plant yields (g m^{-2})	5150.04	3937.73
Efficiency LEDs (g kw h^{-1})	93.92	40.47