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Light-emitting diodes and temperature effects on lettuce growth and its yield in plant factory

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Abstract The study uncovered significant interactions between temperature and light quality, profoundly impacting lettuce growth and yield. Notably, lettuce cultivated under white LED lighting at 25°C demonstrated remarkable characteristics, boasting the highest plant width, height, leaf number, shoot fresh weight, and shoot dry weight, comparable to those under natural sunlight. Among the lettuce varieties, Cos exhibited the most pronounced response in the plant factory, followed by Green Oak, Red Oak, and Butterhead, which showed a more subdued reaction. This underscored the potential of white LED lighting for enhancing crop production efficiency, especially when optimizing growth conditions. These findings provided a valuable insights into the development of future plant factory systems, emphasizing the critical role of tailored environmental control in maximizing agricultural productivity.

Keywords: Plant factory, Light-emitting diode (LED), Lettuce

Introduction

Crop production faces mounting challenges due to global climate change, erratic weather patterns, and water scarcity (FAO, 2009). Simultaneously, the world's population is projected to reach 9 billion by 2050, with 70% residing in urban areas (UN, 2009). To meet the demands of this growing population, a novel approach to agricultural cultivation has emerged: indoor vertical farming, also known as the Plant Factory. This innovative method utilizes artificial lighting to efficiently produce food crops. By arranging cultivation shelves vertically, land utilization is optimized (Kozai, 2013).

Traditionally, fluorescent lamps (FLs) have dominated the plant factory landscape due to their compact design. However, light-emitting diode (LED) lamps are gaining prominence in modern plant factories. Their advantages include compact size, low surface temperature, high light use efficiency, and a

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diverse range of light spectra. Light plays a critical role in plant physiology, morphology, and energy supply for photosynthesis (Taiz and Zeiger, 2002). Notably, red (R) and blue (B) lights significantly influence plant growth and form (Son *et al*., 2012). Combining these wavelengths enhances photosynthetic rates and stomatal conductance across various crops, surpassing the effects of monochromatic R or B light (Matsuda *et al.,* 2007; Hogewoning *et al.,* 2010). White LEDs, with their comprehensive wavelength coverage, offer a valuable tool for plant growth and development (Pimputkar *et al*., 2009).

Beyond light, precise climate control is essential for optimal plant growth in factory systems. In this study, we focus on lettuce as the trial plant. Lettuce exhibits sensitivity to both light and temperature variations. Temperature significantly impacts lettuce production: lower temperatures reduce fresh lettuce weight (Thompson *et al.,* 1998; Choi and Lee, 2004), while higher temperatures lead to bolting, compromising quality and productivity (Fukuda *et al.,* 2009). Outdoor lettuce cultivation typically occurs within a temperature range of 17–22 °C (Thompson *et al.,* 1998), emphasizing the critical role of temperature in lettuce traits. The economic implications are substantial, as temperature control requiring heating and cooling adds to plant factory maintenance costs. Surprisingly, the interaction between growth temperatures and light quality's effects on lettuce production within plant factory systems remains unexplored. Therefore, the study aimed to investigate lettuce growth and yield in response to varying light-emitting diodes and temperatures, with the goal of designing an optimal plant factory system for lettuce production.

Materials and methods

Seeds from four lettuce varieties Butterhead (BH), Red Oak (RO), Green Oak (GO), and Cos (C) were sown in sponge cubes and cultivated hydroponically within a controlled environment. The experimental conditions were meticulously maintained at 25°C with 60-70% relative humidity (RH). A white LED lighting system provided an approximate intensity of 100 µmol m^{-2} s^{-1} photon flux density (PFD) for 16 hours daily. Lettuce seedlings were hydroponically cultivated for 7-14 days and subsequently treated with the SUT-NS5 nutrient solution. This solution comprised essential elements: NO3 (237.84 mg/L), NH4 (30.75 mg/L), H2PO4 (30.04 mg/L), K (290.00 mg/L), Ca (113.56 mg/L), Mg (30.00 mg/L), SO4 (40.00 mg/L), Fe (2.4 mg/L), Mn (1.63 mg/L), Cu (0.125 mg/L), Zn (0.44 mg/L), B (0.51 mg/L), and Mo (0.0225 mg/L). We carefully adjusted the electrical conductivity (EC) to 0.5–0.8 mS and the pH to 5.5–6.5.

After 15 days of growth, the lettuce seedlings were transferred to a vertical hydroponic system. The nutrient solution was renewed weekly, maintaining a pH range of 5.5-6.5 and an EC range of 1.5-1.8 mS. The experiment involved five distinct treatments, each combining different light qualities and temperature conditions: 1) 23°C + Mixed LED: Maintained at 23°C with a mix of white, red, and blue LED lighting in a ratio of 6:4:2. 2)23°C + White LED: Maintained at 23°C with white LED lighting in a ratio of 12. 3) 25°C + Mixed LED: Maintained at 25°C with a mix of white, red, and blue LED lighting in a ratio of 6:4:2. 4) 25°C + White LED: Maintained at 25°C with white LED lighting in a ratio of 12. And 5) Sunlight Control: Natural sunlight was used as a control.

Detailed light spectra are provided in Figure 1. All treatments adhered to a 16-hour photoperiod with a light intensity of approximately 100-120 µmol m^{-2} s^{-1} photosynthetic photon flux density (PFD). Harvesting occurred at 50 days after sowing (DAS).

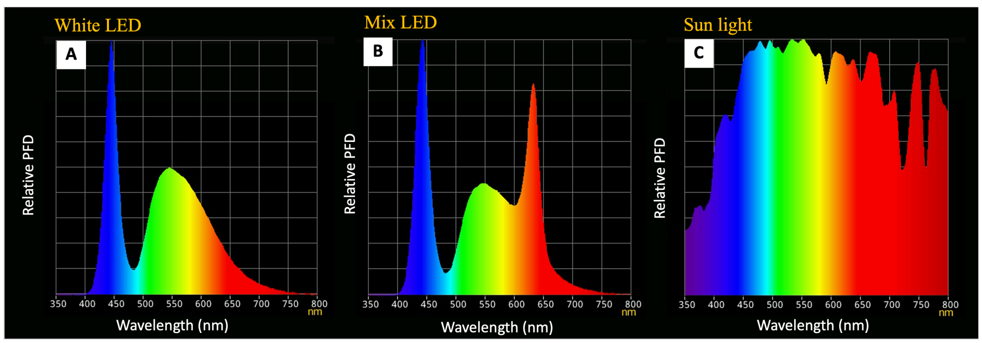

Figure 1. Spectral characteristics of white, white LED light (A), Mix LED light (B) and sunlight (C) used in the experiment

Plant measurements were recorded including height, width, and leaf count every 7 days. Additionally, biometric measurements such as fresh weight (FW), dry weights (DW) of leaves and shoots, and leaf area were conducted at 50 days after sowing (DAS). Chlorophyll readings were obtained using a portable chlorophyll meter (SPAD-502; Minolta, Osaka, Japan). Plant samples were oven-dried at 70°C for 3 days to determine dry weight.

Statistical analyses included analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT). Significance levels were set at $p < 0.05$ and $p < 0.01$. All statistical analyses were performed using SPSS 16.0 software.

Results

Effect of the main factors on plant morphology and growth characteristics

The relationship between lettuce plant growth and the combination of temperature and light quality across five distinct treatments was shown in Figure

1. The findings revealed that maintaining a temperature of 25°C, coupled with both white LED and Mix LED lighting, significantly enhanced average plant height, plant width, and leaf count (Figure 2). This improvement is further reflected in a substantial increased in leaf area compared to the control treatments (Table 1). Notably, under white LED lighting at 25°C, lettuce biomass experienced a remarkable boost, even rivaling the yield which achieved under natural sunlight (control). The preference for monochromatic white LED lighting likely contributed to this growth enhancement, as white LEDs efficiently penetrated the plant canopy, optimizing photosynthesis. This effect was evident in the highest total fresh weight achieved under white LED lighting.

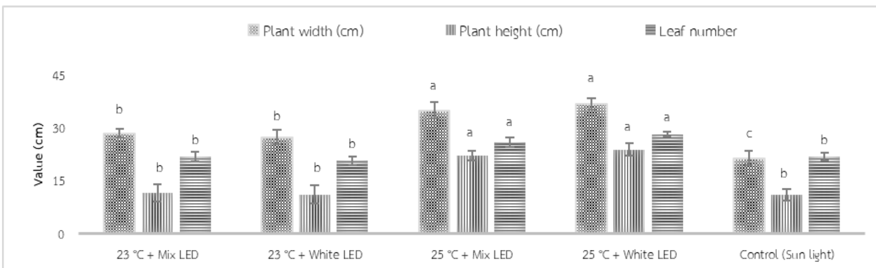

Figure 2. Influence of temperature-combined light quality on lettuce plant width, plant height, and leaf number at 50 days

Table 1. Effect of temperature and light quality on leaf area (LA), total fresh weight (FW), total dry weight (DW), and SPAD value of lettuce at 50 days

Treatment	LA (cm^2)	FW (g)	DW (g)	SPAD
23°C + Mix LED	1524.70±247.70^{b} [1/]	61.61±12.74^{c}	2.24±0.33^{c}	24.50±2.78^{b}
23°C + White LED	1271.50±191.98^{b}	58.68±10.30^{c}	1.96±0.29^{c}	24.04±2.82^{b}
25°C + Mix LED	2054.50±279.43^{a}	83.95±24.02^{b}	2.53±1.41^{c}	24.41±2.15^{b}
25°C + White LED	2246.30±152.89^{a}	102.61±8.81^{a}	3.33±0.23^{b}	25.09±2.79^{b}
Control (Sunlight)	1535.50±170.49^{b}	113.07±9.28^{a}	7.11±0.27^{a}	29.22±2.91^{a}

[1/] Presented data as means ± SE. Data not followed by the same letter in a column are significantly different ($P < 0.01$) based on DMRT.

The impact of different temperature and light quality combinations on the growth of four lettuce varieties: butterhead (BH), red oak (RO), green oak (GO), and cos (C) was shown in Figure 3. Each variety's morphology responded distinctly to vary the temperature and light conditions. Cos lettuce exhibited the most favorable morphological attributes, while red oak lettuce displayed unique leaf color expressions (Figure 4).

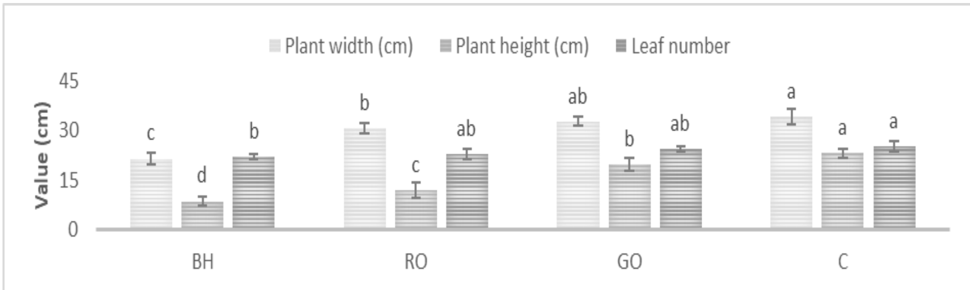

Figure 3. Influence of four lettuce varieties (butterhead (BH), red oak (RO), green oak (GO), and cos (C)) on plant width, plant height, and leaf number at 50 days

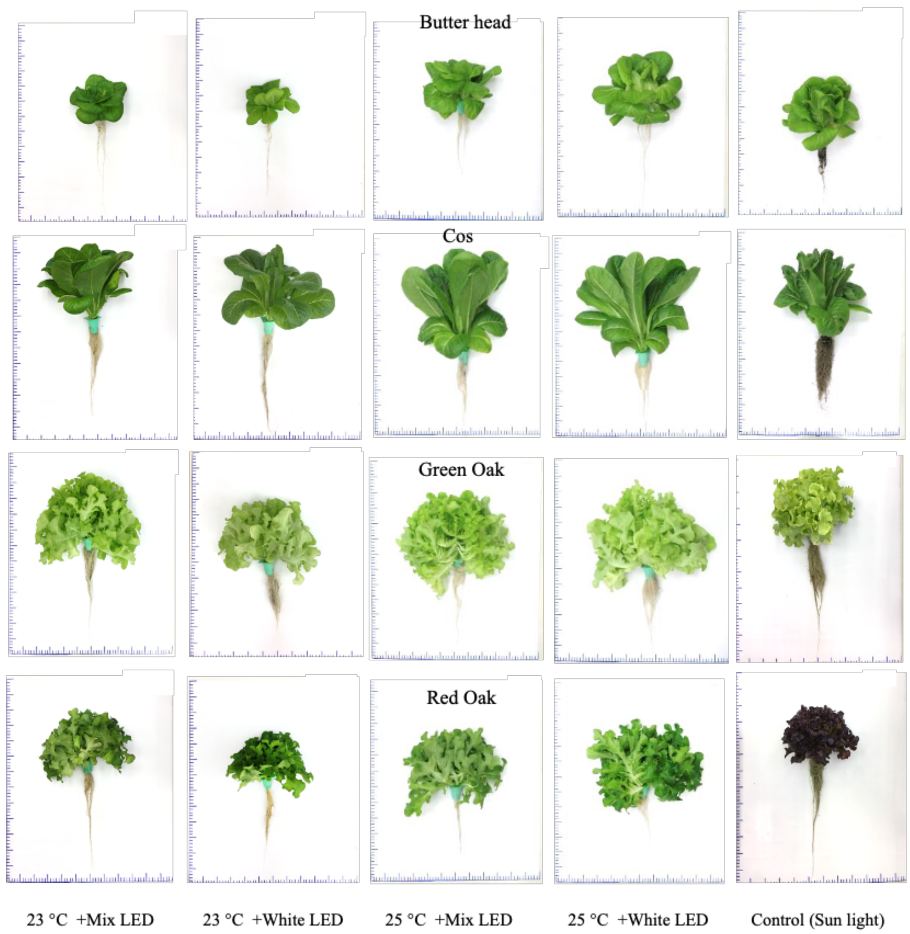

Figure 4. Effect of temperature and light quality on lettuce varieties at 50 days after sowing

Biomass measurements across all four lettuce varieties were subjected to different temperature and light conditions (Table 2). Highly significant differences ($P < 0.01$) are observed across multiple parameters, including leaf and shoot fresh weights, dry weights, leaf area, and SPAD readings. Among the four varieties, cos lettuce demonstrated the most pronounced growth response, followed by green oak, red oak, and butterhead, which exhibited a more subdued reaction to the conditions.

Table 2. Effect of temperature and light quality on leaf area (LA), total fresh weight (FW), total dry weight (DW) and SPAD value of lettuce at 50 days

Variety	LA (cm^2)	FW (g)	DW (g)	SPAD
Butter head	805.48±137.57^{c}[1/]	34.28±6.23^{d}	1.42±0.22^{c}	25.28±0.91^{c}
Rad Oak	1664.80±112.45^{b}	70.02±5.22^{c}	3.24±0.37^{b}	26.54±0.67^{b}
Green Oak	2167.20±170.61^{a}	96.29±7.59^{b}	3.56±0.54^{b}	12.60±0.73^{d}
Cos	2269.30±158.40^{a}	135.06±15.91^{a}	5.52±1.18^{a}	37.38±0.38^{a}

[1/] Presented data as means ± SE. Data not followed by the same letter in a column are significantly different ($P < 0.01$) based on DMRT.

Effect of interaction between lettuce varieties and temperature-light quality

The interaction effect between lettuce varieties and varying combinations of temperature and light quality indicated a significant interaction ($P < 0.01$) between these two factors regarding growth and yield. Among the tested treatments, maintaining a temperature of 25°C in conjunction with white LED lighting consistently yields the highest growth and yield for all four lettuce varieties (Figure 5 and Table 3). Specifically, butterhead lettuce exhibited a plant height of 15.67 cm, 31 leaves, a leaf area of 1548.60 cm^3, and a total fresh weight of 72.63 g. Cos lettuce displayed a plant width of 39.67 cm and a plant height of 33.67 cm. Green oak lettuce had a plant width of 40 cm, a plant height of 28.33 cm, 32 leaves, and a leaf area of 2902.40 cm^3. Lastly, red oak lettuce showed a plant width of 38.33 cm and a plant height of 17.67 cm. Interestingly, total dry weight and chlorophyll readings (SPAD) in the sunlight treatments surpassed those in the LED lighting treatment and the temperature control (Table 3).

Table 3. Influence of lettuce varieties (butter head, red oak, green oak, and cos) under different temperature and light quality conditions on leaf area (LA), total fresh weight (FW), total dry weight (DW), and SPAD readings at 50 days

Factor A x B		**LA (cm^2)**	**FW (g)**	**DW (g)**	**SPAD**
Variety	**Treatment**				
Butter head	23 °C + Mix LED	681.72±59.14^{bc}[1/]	24.01±3.96^{b}	1.14±0.10^{b}	24.07±1.27^{b}
	23 °C + White LED	391.54±54.84^{c}	16.39±5.49^{b}	0.63±0.13^{b}	22.50±0.17^{b}
	25 °C + Mix LED	1076.40±239.07^{ab}	39.13±10.51^{b}	1.33±0.49^{b}	24.15±1.45^{b}
	25 °C + White LED	1548.60±273.45^{a}	72.63±11.16^{a}	2.57±0.57^{a}	24.54±1.91^{b}
	Control (Sun light)	329.15±48.44^{c}	19.26±3.08^{b}	1.42±0.08^{a}	31.13±0.03^{a}
Cos	23 °C + Mix LED	1774.00±74.52^{bc}	84.70±3.40^{b}	2.99±0.08^{b}	37.87±0.65
	23 °C + White LED	1583.40±295.31^{c}	89.00±16.43^{b}	2.85±0.31^{b}	37.80±2.05
	25 °C + Mix LED	2682.40±251.34^{a}	135.06±16.05^{b}	3.53±0.52^{b}	36.62±0.11
	25 °C + White LED	2457.90±279.19^{ab}	132.10±23.84^{b}	4.05±0.8^{b}	37.21±0.33
	Control (Sun light)	2848.50±136.18^{a}	234.45±11.56^{a}	14.19±0.67^{a}	37.40±0.10
Green Oak	23 °C + Mix LED	1958.70±51.07^{ab}	78.37±18.91	2.42±0.22^{b}	11.90±0.47^{b}
	23 °C + White LED	1686.40±103.67^{b}	74.36±6.93	2.23±0.36^{b}	11.10±1.11^{b}
	25 °C + Mix LED	2526.00±630.64^{ab}	89.46±24.09	2.44±0.61^{b}	10.93±0.53^{b}
	25 °C + White LED	2902.40±175.83^{a}	121.84±12.50	3.59±0.17^{b}	11.32±0.27^{b}
	Control (Sun light)	1762.60±126.94^{b}	117.41±12.80	7.10±0.98^{a}	17.77±0.03^{a}
Rad Oak	23 °C + Mix LED	1684.50±97.46^{ab}	59.36±9.78	2.40±0.41^{b}	24.17±0.47c
	23 °C + White LED	1428.50±65.53^{ab}	54.97±17.96	2.16±0.81^{b}	24.77±10.64^{bc}
	25 °C + Mix LED	1932.90±194.23^{a}	70.72±14.54	2.83±0.47^{b}	25.91±0.77^{bc}
	25 °C + White LED	2076.40±362.94^{a}	83.88±15.57	3.11±0.51^{b}	27.27±0.51^{b}
	Control (Sun light)	1201.90±98.17^{b}	81.16±9.84	5.71±0.56^{a}	30.57±0.27^{a}

[1/] Presented data as means ± SE. Data not followed by the same letter in a column are significantly different ($P < 0.05$) based on DMRT.

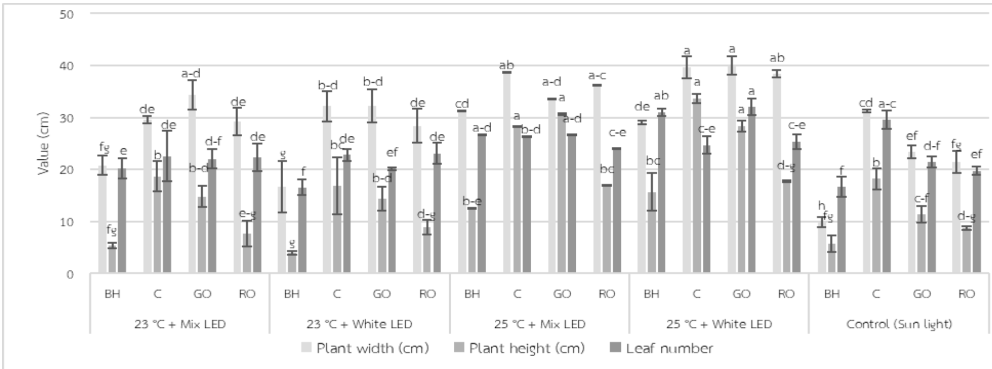

Figure 5. Impact of temperature and light quality on lettuce varieties (butterhead (BH), red oak (RO), green oak (GO), and cos (C)) on plant width, plant height, and leaf number at 50 days

Discussion

The study highlighted the significant impact of temperature, light quality, and their interaction on lettuce growth, chlorophyll content, and yield. Specifically, it observed positive effects on lettuce growth under four treatments: 23°C with Mix LED, 23°C with White LED, 25°C with Mix LED, and 25°C with White LED. Notably, the combination of 25°C temperature and white LED lighting induced the most substantial improvements in plant width, plant height, leaf number, and leaf area. This enhancement can be attributed to the lower temperature compared to the control treatment, resulting in a higher fresh weight yield. Previous research by Pyo-Hwan *et al.* (2011) demonstrated that optimal lettuce growth occurs at 25°C in a plant factory. However, it's essential to recognize that lettuce's response to temperature is cultivar-specific (Al-harbi, 2001). Wallace *et al.* (2012) reported that lettuce's optimal growth temperature lies around 18.5°C, with flower initiation typically occurring between 21°C and 27°C.

In contrast, lettuce grown under natural sunlight significantly influenced chlorophyll content (SPAD) and total dry matter compared to LED light. Light intensity plays a critical role in photosynthetic efficiency under varying light and temperature conditions. The reduction of light intensity can limit carbon assimilation enzyme activity, affecting plant carbon assimilation. Conversely, the elevated light intensities stimulated photosynthesis, leading to enhance biomass production. However, low light is often intensitied to induce photoinhibition, negatively impacting plant photomorphogenesis (Chen *et al.,* 2017). Consequently, SPAD values and total dry matter are notably reduced, particularly under LED light treatment. Plants exposed to low light intensity typically exhibited lower photosynthetic efficiency and biomass production (Fu *et al.,* 2012).

The study revealed diverse coloration patterns in Red Oak lettuce cultivars as they progressed through different growth stages. Leaves growing outdoors tended to display a darker, reddish hue, while those exposed to LED lighting consistently exhibited brighter, greener, and more yellowish tones across all LED light conditions. The concentration and distribution of chlorophylls and anthocyanins are significantly contributed to leaf color (Gazula *et al.,* 2007). Environmental factors such as light intensity, quality, duration, and temperature may play pivotal roles in regulating pigment accumulation. However, the results suggested that the experimental conditions may not develop the red leaves, likely due to a combination of factors.

Fresh weight was significantly influenced to consumer preferences. Therefore, when aiming for maximum weight in plant cultivation, considering planting under conditions that optimize growth, such as a combination of 25°C temperature and white LED lighting. This approach may offer potential benefits for cultivating various lettuce varieties.

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